India in the Space Age

Mohan Sundara Rajan

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MOHAN SUNDARA RAJAN

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FOREWORD

Space exploration has been a fascinating story and continues to excite every one. The benefits of these explorations have been realised in terms of services like communication, television broadcasting, meteorology, disaster warning, resources survey and management. India was one of the earliest to realise the potential of space for national development. Starting with modest sounding rockets launched from near Thiruvananthapuram, India has come a long way in developing indigenous satellite systems like INSAT and IRS, besides launching these satellites using its own launch vehicles like Polar Satellite Launch Vehicle and Geosynchronous Satellite Launch Vehicle. What is more striking has been the application in which space systems in the country have been used. In recent years, besides routine use of the space systems for tele-communication, television broadcasting, meteorology, disaster warning, resources survey and management, they are being used for innovative applications like telemedicine and Village Resource Centres.

While efforts in designing, developing and establishing the space systems and utilising them are important, it is equally essential to make the common man understand some of the nuances of the exciting space systems and the benefits that he is deriving from them. Shri Mohan Sundara Rajan has been making efforts precisely in this area as a good communicator. He has been pursuing the developments in space programme very closely and he can make a general reader appreciate and understand the basic technologies involved in various elements of the space system and, at the same time, convey how the Indian space proguamme has been benefiting the common man.

In this book, Shri Mohan Sundara Rajan has brought out the achievements in the Indian space programme. I am sure that the readers will find this book informative.

Bangalore

G Madhavan Nair
Chairman
Indian Space Research Organisation

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The countdown for the launch of my books on Space was propelled by my TV interviews with Neil Armstrong, the first man on the moon and his astronaut colleagues, Charles Conrad and Walter Schirra as well as Russian cosmonauts B.N. Voynov, Y.V. Khrunov and Boris Yegorov, the first doctor-cosmonaut.

I had the privilege of receiving a commendation from the legendary science writer, Arthur C. Clarke, for my book, Wonders of Space.

I have also had the privilege of interviews with the late Dr Vikram Sarabhai. Later, Prof Satish Dhawan encouraged me to write my first book on the Indian space effort by arranging for my travel and interviews with a wide range of scientists and engineers across the various centres of ISRO. His foreword to my book *India in Space*, brought out by the Publications Division, was appreciated by the late President Fakhruddin Ali Ahmed, when he released it and called for its translation into various languages.

The late Prime Minister, Smt Indira Gandhi released the Urdu version.

I thank Prof U.R. Rao and Dr K. Kasturirangan, eminent scientists and former Chairmen of ISRO and their illustrious successor, Mr G. Madhavan Nair for their consistent encouragement. I benefited from my discussions with their colleagues: Dr B.N. Suresh, former Director, Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram; Dr K.N. Shankara, Director, ISRO Satellite Centre (ISAC); Mr Sundararamaiah, Scientific Secretary, ISRO; Dr M.Y.S. Prasad, Deputy Director Satellite Applications Centre, Ahmedabad; Dr K. Radhakrishnan, Director, VSSC; Dr G. Viswanathan, Director, ISRO Radar Development Unit; Dr V. Jayaraman, Director, Earth Observation Systems; Mr S.V. Kibe, Director INSAT Programmes: Mr P. Soma, Group Director, ISRO Telemetry, Tracking and Command Network, Bangalore; Mr V. R. Katti, Programme Director, Geosat, ISAC; Dr C.G. Patil, Director, Master Control Facility, Hassan; Mr R.K. Rajangam, Project Director INSAT 4B; Mr D. Narayana Moorthy, Visiting Scientist; Mr N. Narayana Moorthy, Project Director (PSLV); Dr George Joseph, Director, Centre for Space Science

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Mohan Sundara Rajan

PREFACE

This book tells an up-to-date story of India's emergence as a space power, as the world celebrated the golden jubilee of the Space Age in 2007. Recalling the role of Vikram Sarabhai and Satish Dhawan, the story traces the humble beginnings of the space effort on the shores of Thumba and goes on to narrate the ventures of the pioneers in climbing the learning curve, braving the inevitable setbacks only to achieve perfection in the rockets that launch satellites into sunsynchronous and geosynchronous orbits. A brief introduction explains the nuances of these orbits and how India's young scientists and engineers have mastered the technology of stabilising the rockets and satellites. The story then describes the ongoing efforts to perfect the cryogenic engine and stage for a totally indigenous geosynchronous launch vehicle to orbit future INSATs.

The next Part takes the reader through the transition from the times when the first series of INSATs was made abroad to the days when the ISRO started to make the more complex satellites at home. The indigenous satellites included those for remote sensing natural resources from the polar sunsynchronous orbits. A separate chapter explains the amazing application of sensors that capture the real status of the resources from space resulting in world class imageries that are in demand at home and abroad. This is followed by an introduction to the various resource satellites including the latest Cartosats that constitute the world's largest array of such satellites.

The subsequent chapters describe the services provided by the INSATs like direct-to-home television, telecom and data links as well as weather monitoring and forecasts, indicating the contours of the revolution on the ground in the collection and distribution of information, in multimedia entertainment, business and services and in air navigation. The next few chapters present examples of using the remote sensing satellite data in addressing a variety of problems in irrigation, farming, flood control and development planning. In fact, the satellites have rediscovered India, revealing the true state of its natural resources.

The story then explains India's first moon mission, Chandrayaan-1, and the country's first astronomy mission, Astrosat, followed by the role of Indians who had been explorers in space.

With the rapid advances in space technology and applications, a story that captures their role also gains in depth. Accordingly, several new technological challenges have been explained in non-technical terms for the benefit of the lay reader.

Mohan Sundara Rajan

CONTENTS

PART - I

A GOLDEN JUBILEE

1. Trends in the Space Age

The Space Age began on October 4, 1957, when the Russian unmanned satellite, Sputnik-1, went into Earth orbit, jolting the world. Little did people imagine that the technological innovation would soon make profound changes in their daily lives.

Sputnik-1 actually stopped transmitting after 22 days and re-entered the Earth's atmosphere after three months, burning up on January 4, 1958. But it proved that an artificial satellite can go into orbit around the Earth, if it reaches a speed at 29,000 km an hour. The temperature and pressure that it encountered in the upper layer of the atmosphere were encoded in the duration of radio beeps. Science fiction on going into space became science.

Though Sputnik-1 started a space race between the then Soviet Union and the United States as part of the Cold War, the very rockets that were dreaded as weapons of destruction soon launched satellites of increasing complexity for communication, weather, reconnaissance and remote sensing. The emergence of the integrated circuit, extraordinary electronic memory, increasingly user-friendly computers, and the Internet imparted unexpected slingshots to the trajectory of space technology towards a new era of information and entertainment. Never before in history, an audience of billions across continents simultaneously experienced the thrill of a world sporting event. Never before could people be in constant touch with others even on the other side of the world. Never before was there even an attempt to provide telecommunication to anyone, anywhere, at any time, subject only to the ground infrastructure.

The extraordinary developments are not confined to the developed world. Developing countries, especially India, have made a leapfrog into the Space Age and shown how it can be used for making up centuries of backwardness.

India today is one of the few countries in the world for grassroot application of space technology. The country has an innovative framework for dealing with space applications – a task that involves not only the government but a large user community.

If India today can be counted as a space power, as it has the capability to design, develop, launch and maintain satellites in near Earth, it is largely due

to the founding fathers of the space programme, Vikram Sarabhai and Satish Dhawan. Thanks to their vision and mission, India has been in the forefront of bringing the benefits of space technology to the comman man.

A distinguished space scientist, Aravamudhan, has called the first ten years of ISRO (1963-1973) as the Vikram Sarabhai decade, a decade of vision, dreams and hopes.

Vikram Sarabhai: Architect of India's Space Programme

A distinguished audience, which included the former Prime Minister Mrs Indira Gandhi, was present in Thumba in 1968 to witness the launch of a sounding rocket. The scientist in charge was cautioned that for the previous 100 years, it had rained at that time in Thumba and that he was taking a risk in organising the launch. His typical answer was "Why can't the 101st year be different?" And he went ahead. To everyone's delight, there was no rain and all three rockets were launched successfully. The scientist was none other than Vikram Sarabhai (1919-1971), architect of India's space programme. Thinking differently was his hallmark.

The same streak of original thinking marked his foresight on the relevance of the Space Age to a developing country like India at a time when space was a new luxury for the rich countries. Even before the Space Age, he was interested in the study of cosmic rays which was at the frontiers of science. His multifaceted character found its expression in extending the benefits of science to all aspects of socio-economic development.

It was a happy coincidence that Sarabhai found in Pandit Nehru and later in Mrs Gandhi whole-hearted support for his approach to space technology. Equally important was Sarabhai's uncanny ability to spot talent and nourish it.

He was quick to see windows of opportunity and grab them, as was amply brought out by his plan to use an American satellite for the famous SITE experiment to prove the value of space technology for developing countries.

Sarabhai's sheer boldness in taking on the big powers impressed everyone. Addressing the United Nations Conference on the Exploration and Peaceful Uses of Outer Space in 1968, Sarabhai stated:

"A developing nation following a step-by-step approach towards progress is landed with units of small size, which do not permit the economic deployment of new technologies. A positive approach out of this predicament seems to lie in finding solutions where the particular disadvantage of developing nations, which is that they have little to build on, is made an asset rather than a liability. ... One is often told that such and such a thing is too sophisticated to be applied. This approach disregards what should perhaps be obvious, that when a problem is great, one requires the most effective means available to deal with it."

Sarabhai's words of wisdom in using space technology continue to be relevant today. *"There is a totality about the process of development,"* he said, *"which involves not only advanced technology and hardware but imaginative planning of supply and consumption centres, of social organization and management to leapfrog from a state of backwardness and poverty. ... We are convinced that we must be second to none in the application of advanced technologies to the real problems of man and society which we find in our country."*

Sarabhai emphasised that the mass media should convey the human story of a developing country with very little infrastructure mastering something like space technology and its application. Media attention should not be confined to spectacular events like a rocket launch or projects.

Sarabhai was a pragmatic visionary. He had established the Indian Institute of Management and Physical Research Laboratory, both at Ahmedabad and nurtured some 30 institutions and industries, including cultural establishments. He had envisaged the role of computers, even a decade before the Internet surfaced.

Remembering Sarabhai today raises the question whether his ideals have been fully realised. Though many of the technologies which he envisaged have been proved, a time has come when ISRO alone cannot ensure the full use of the means it has operationalised. In fact, not all departments readily took to the culture of planning on the basis of data collected from space. What is required today are innovative solutions, which are specific to the region or district utilising what satellites can offer in the field of remote sensing, communications, education, health and entertainment.

More basically, what is required is widespread interest in space itself at the school and college level. It is a pity that only one or two out of every ten post-graduates are aware of some basic features of the Indian space effort. In contrast, the curiosity of young children at school to know about the wonders of space and applications is widespread. We need a nationwide campaign to "catch them young" and encourage popular science about space, free from the pain of learning it for examinations.

The second 10 years (1973-1983) has been described as the decade of Satish Dhawan, when programmes were consolidated. And equally significant are the contributions of innumerable faceless engineers, scientists and technicians, both in the public and private sectors to make the space programme a success.

Satish Dhawan : An Outstanding Space Scientist

If Vikram Sarabhai is admired as a visionary, Satish Dhawan (1920-2002) could well be regarded as a missionary who realised Sarabhai's dream. Dhawan's role in consolidating the space activities has been crucial to the emergence of India as a Space Power.

Dhawan was born on September 25, 1920 in Srinagar. He graduated from the University of Punjab with an unusual combination of subjects: B.A. in Mathematics, M.A. in English literature and B.E. in Mechanical Engineering. He went to the United States and did M.S. in Aeronautical Engineering in the University of Minnesota. He then went to California Institute of Technology and took Ph.D. in Aeronautics and Mathematics in 1951.

Returning to India, Dhawan joined the Indian Institute of Science (IISc) as a Senior Scientific Officer. In 1955, he became Professor and Head of the Department of Aeronautical Engineering of IISc. In 1962, he became the youngest Director of the IISc at 42. During his tenure as Director, he went to Caltech on a sabbatical, when he got a call from the Prime Minister, Indira Gandhi, to return home and head the space activities, following the death of Vikram Sarabhai on December 30, 1971. However, he replied that he could come only after he finished some academic work and that too if the IISc management permitted him. The Prime Minister decided to wait.

In May 1972, the Department of Space and the Indian Space Research Organisation (ISRO) were constituted and the subject of Space was transferred from the Department of Atomic Energy. As insisted by Dhawan, he was allowed to continue as Director of the IISc even as he became the Chairman of the Space Commission and ISRO as well as Secretary of the Department of Space with headquarters in Bangalore. Even after retirement in 1984, he continued as Member of the Space Commission. He passed away in January, 2002.

Dhawan is regarded as the founder of experimental fluid dynamics research, involving wind tunnels. He was keen to develop low-cost indigenous equipment with whatever materials and skills were available.

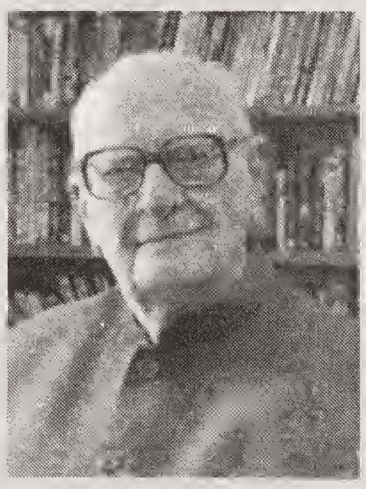
He endeared himself to all by his style of administration, giving due credit for the success of a project to the project director and his team, while taking upon himself the blame for any failure. He richly deserved the Indira Gandhi Award for National Integration, as ISRO is a symbol for bringing together people from various parts of India to work for national goals. Above all, he remained a humanist.

An ardent lover of Nature, he was fascinated by birds in flight. He authored a monograph on the subject.

On the occasion of the golden jubilee of the Space Age, it would be appropriate to recall the views of Arthur C. Clarke, one of the outstanding science writers of the world, who predicted in 1945 (long before the Space Age) the geosynchronous orbit, in which satellites like the INSAT today function.

ARTHUR CLARKE'S PROPHESY

The geostationary orbit is also known as the Clarke orbit, in honour of Arthur C. Clarke, the famous British science fiction writer, who envisaged it in 1945 long before the Space Age. His now-famous article in the *Wireless World* in October 1945 predicted extra terrestrial relays, combining rocketry, wireless communication and radar. One of his famous "laws" is: when a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong!



During his visit to India in 1971, Clarke gave me an interview on Delhi television. I was struck by his familiarity with the developments

in India relating to space science and technology: Thumba, the world's first ground-based sounding rocket range, had by then become operational; India's first rocket Rohini-75 had been launched; and plans were drawn up to orbit a scientific satellite using India's own rocket called SLV-3.

Clarke predicted that India would be using the geosynchronous orbit sooner than expected. He welcomed India's initiative in preparing an experiment with an American satellite in geosynchronous orbit to evaluate the transmission of television to 5000 villages across the country.

What impressed him most in making his prophesy about India was the sheer range of activities undertaken in different parts of the country by dedicated groups of scientists. For example, in Ahmedabad Indian engineers had built an earth station to link with satellites in a record time of 87 days, with some assistance from international organisations.

When I hesitated to describe the small dimensions of India's first rocket, he pointed out what was critical in these matters was getting the correct idea, as proved by his own prophesy. He was impressed with the dedication of the pioneering space scientists in India in accepting the challenge of mastering new ideas and hoped that the younger generation would continue to imbibe the pioneering spirit of Vikram Sarabhai.

Speaking on Indian television in an interview with the author, Clarke was quite hopeful that India would take advantage of the Space Age. He was aware of the launch of Rohini-75, India's first rocket, ridiculed at home by some as a toy rocket. It requires a perceptive mind to sense the capability of a nation in launching innovative schemes. Today, ISRO has fulfilled Arthur Clarke's hopes.

A golden jubilee of a great innovation is an appropriate occasion to embark on a technological roadmap in line with the best practices in the world. Reusable rockets and nano satellites are emerging. And each generation has to master ever-new technologies and redefine their goals in accordance with the needs of the society. The jubilee is also the time to take stock of the impact of the technology and profit by the lessons learnt.

While doing such an appraisal, one basic factor needs to be kept in view: technology often runs ahead of social, economic and political institutions. Technocrats alone cannot deliver the goods. Public awareness, understanding and cooperation to space programmes are essential prerequisites for success.

A priority area where space technology needs to be applied is safeguarding national resources. One of the greatest gifts of the Space Age is its reminder that the Earth is a rare blue jewel, whose environment cannot be taken for granted. Satellites have revealed disturbing ground truths about the state of our natural resources, even as the birds in the sky trigger hopes of reclamation and recovery, given the popular support.

In meeting the challenge of taking the technology to the people, a new kind of leadership is required. As stated by Dr Abdul Kalam,

"*We have to create a new stream of creative leaders, whose leadership styles move from commander to coach, manager to mentor, from director to delegator and from one who demands respect to one who facilitates self-respect.*"

Basically, developments in space technology and its applications have originated from innovative minds that have ventured out to try new ideas. It is essential that the country's younger generation is encouraged to nurture a sense of curiosity which triggers new ideas. A liberal mindset is the best launching pad for novel, if strange, ideas, as exemplified by Aryabhata, one of the greatest astronomers the world has ever seen, who thought differently and acted against the mainstream of ideas.

Aryabhata

India's Aryabhata (born in 476 AD) was an intellectual rebel. He was 23, when he became famous. The well-known Persian scholar, Al-Biruni (973-1048) referred to him as Aryabhata 1 of Kusumapura, which is now Patna in Bihar. Aryabhata rejected the *puranic* idea of creation and destruction of the universe. According to him, time has neither a beginning nor an end; it is *anaadi* and *ananta*.

About a thousand years before Copernicus, he declared in beautiful verse that the Earth rotated on its axis and went around the Sun. Aryabhata explained it in simple terms and with an ordinary example. He said, "Just as a man in a boat moving forward sees the stationary objects on either side of the river as moving backward, just so are the stationary stars seen by the people at Lanka (the equator) moving exactly towards the west." He boldly described the Earth as spherical, 'circular in all directions'.

Aryabhata did not merely give ideas. He calculated, for example, the duration of a sidereal day (with reference to fixed stars in the sky). He pointed out that a *yuga* consisted of 1 57 791 7500 days, which when divided by the number of the Earth's revolutions during that

period (1,582,237,500), yields a day's duration of 23 hrs, 56 minutes and 4.1 seconds, which is amazingly close to the modern estimate of 23 hrs, 56 minutes and 4.091 seconds!

His findings in trigonometry and astronomy enabled him to calculate the distance travelled by celestial bodies in a yuga. The path of the annual motion of the Sun among the stars, its inclination to the celestial equator and the resultant difference in the duration of night and day in the northern and southern hemispheres at different times of the year were known to Aryabhata, who gave formulae to calculate the differences according to the latitude of a place.

He had a unique system of representing large numbers by alphabets in poetry, with amazing brevity of expression, a factor which might have proved too difficult for his followers. Nevertheless, he had generations of admirers and followers. The most noted among them is Bhaskara I, who composed his commentary of *Aryabhatium* in 629 AD. Bhaskara on his own made significant contributions to mathematics and astronomy. He obtained the mean celestial longitudes of planets by a simple and short-cut technique. His works have been well known among astronomers for centuries, especially in Kerala.

Aryabhata's rational ideas did not find favour with the conservatives of his time. The conservative current was so strong that even in later years, Aryabhata had his share of opponents. Varahamihira (d 587) and Brahmagupta (628 AD) criticised him. But eventually truth prevailed and Aryabhata shines as a diamond forever!

His rational division of time was also remarkable. One *maha yuga,* he said, consisted of 4,320,000 years and 72 maha *yugas* equalled one manu and 14 manus or 1008 yugas added up to what he called a *kalpa*. It is also known as a day of *Brahma. A kalpa* will be about 4320 million years, which is close to the modern estimate of the age of the Earth, when conditions favoured primitive life forms. He subdivided a *maha yuga* into four parts, viz. *Krta, Treta, Dvapara* and *Kali* but of equal duration (1,080,000 years), unlike their traditional division in the ratio of 4:3:2:1

2. New Ideas in an Ancient Land

Ancient India had an admirable record of intellectual accomplishments. In the words of the famous French mathematician Laplace (1749-1827), "It is India that gave us the ingenious method of expressing all numbers by means of 10 symbols, each receiving a value of position as well as an absolute value. The idea escaped the genius of Archimedes and Apollonius." The well-known historian, A.L. Basham, observes that the unknown Indian who invented the concept of zero deserves the gratitude of mankind for ever. India's traditional calendars predict the transit of planets, the sun and the moon accurately. And lakhs and lakhs of people become aware of the predicted celestial events even in the absence of modern mass communication.

It is now established that the so-called Pythogoras' Theorem attributed to the Greek scholar of the 6th century BC (according to which the square of the hypotenuse of a right-angled triangle is equal to the sum of the squares on the other two sides) was well known to the authors of Sulva Sutras appearing in Vedic mathematics. Present day scholars have therefore a strong case to rename the Pythogoras' Theorem as Sulva Theorem!

One of India's greatest astronomers and mathematicians, Aryabhata-I in the fifth century AD gave for the first time the value of π correct to four decimal places. What is more, he indicated that the value was only approximate, a fact that was proved only in the 18th century in Europe. Ancient Jain texts also contain detailed calculations of π.

Aryabhata was not only a revolutionary astronomer but was also regarded as the father of algebra. He has, for instance, given the tables for the trigonometric ratio 'sine' for numerous angles.

He also explained the phenomena of the solar and lunar eclipses scientifically. For instance, he stated simply that the Moon covers the Sun and the great shadow of the Earth eclipses the Moon. Later in the 6th century AD Varahamihira demolished the myth of a demon causing the eclipse by stating that at a lunar eclipse the Moon enters the shadow of the Earth and at a solar eclipse, it covers the Sun's disc.

The application of modern instruments to foster a spirit of inquiry was however slow and sporadic in the country until its Independence. The use of the telescope had to await the arrival of ships operated by the East India Company. Long sea voyages kindled interest in astronomy. In 1972, an observatory was set up in Chennai when interestingly, Indian rockets, though uncontrolled, pounded the British in battles near Mysore.

By then the nucleus of what eventually became Survey of India was established. After about a century, the Madras Observatory was shifted to the hills of Kodaikanal in Tamil Nadu. A Solar Physics observatory was set up in 1899. Photographs of the Sun were regularly taken from 1904. It was from India that helium in the Sun was discovered.

In the early nineteenth century, the Colaba Observatory was started in Mumbai. In 1825 the Indian Meteorological Department was set up. Another significant development was the study of the ionosphere by Indian scientists, very soon after its discovery. Dr Meghnad Saha (1893-1956) studied the spectra of the Sun and stars and outlined his theory of ionization, which later enabled astronomers to detect the presence of various elements in celestial objects. There was research on the physics of the upper atmosphere in some universities. Cosmic ray research was done at Aligarh and Kolkata. Dr Homi Bhabha (1909-1966) studied cosmic rays at the Indian Institute of Science, Bangalore in the 1940s. Dr Vikram Sarabhai (1919-1971) was also attracted by the subject when he was working with the Nobel Laureate, Dr C.V. Raman (1888-1970) in Bangalore. Later Dr Sarabhai set up a research laboratory in Ahmedabad in 1947. After Independence in 1947, several national laboratories were set up to conduct research on a wide variety of subjects. The National Physical Laboratory, New Delhi, started, among others, studies on ionospheric physics.

Dr Sarabhai's research laboratory was expanded into the Physical Research Laboratory, Ahmedabad in 1948, and cosmic ray research was continued. The subjects studied extended to such areas as ozone in the upper atmosphere. In the early 1950s, there were ground-based studies on the ionosphere and magnetosphere with balloon-borne experiments. Scientists in India were ready with new ideas when the Space Age dawned in 1957. The success of the Sputnik (Russian for satellite) and the discovery of radiation belts surrounding the Earth by America's first satellite, Explorer-1 opened a new era of research in space. The satellite became a reality and outer space attracted further exploration.

In 1961 the Department of Atomic Energy in India was entrusted with the subject of peaceful uses of outer space. A year later, the Indian National Committee for Space Research (INCOSPAR) was set up with Dr Sarabhai as Chairman, to advise the government on space research and foster international co-operation in the field. The Committee's first major suggestion was the setting up of a sounding

rocket range in Thumba, on the west coast in Kerala near Thiruvananthapuram, close to the Earth's magnetic equator.

Located at 8°32'34" north of the geographical equator and at 76°51'32" E longitude, Thumba is less than a degree (O°24' N) away from the Earth's magnetic equator. At the magnetic poles, which are slightly shifted away from their geographical counterparts, a magnetic needle will be perpendicular to the horizontal, when freely suspended. Near the Earth's equator, there are points where the needle becomes perfectly horizontal. An imaginary line on the surface of the Earth connecting all such points is called the magnetic equator. It passes close to the geographical equator.(Fig 1.1)

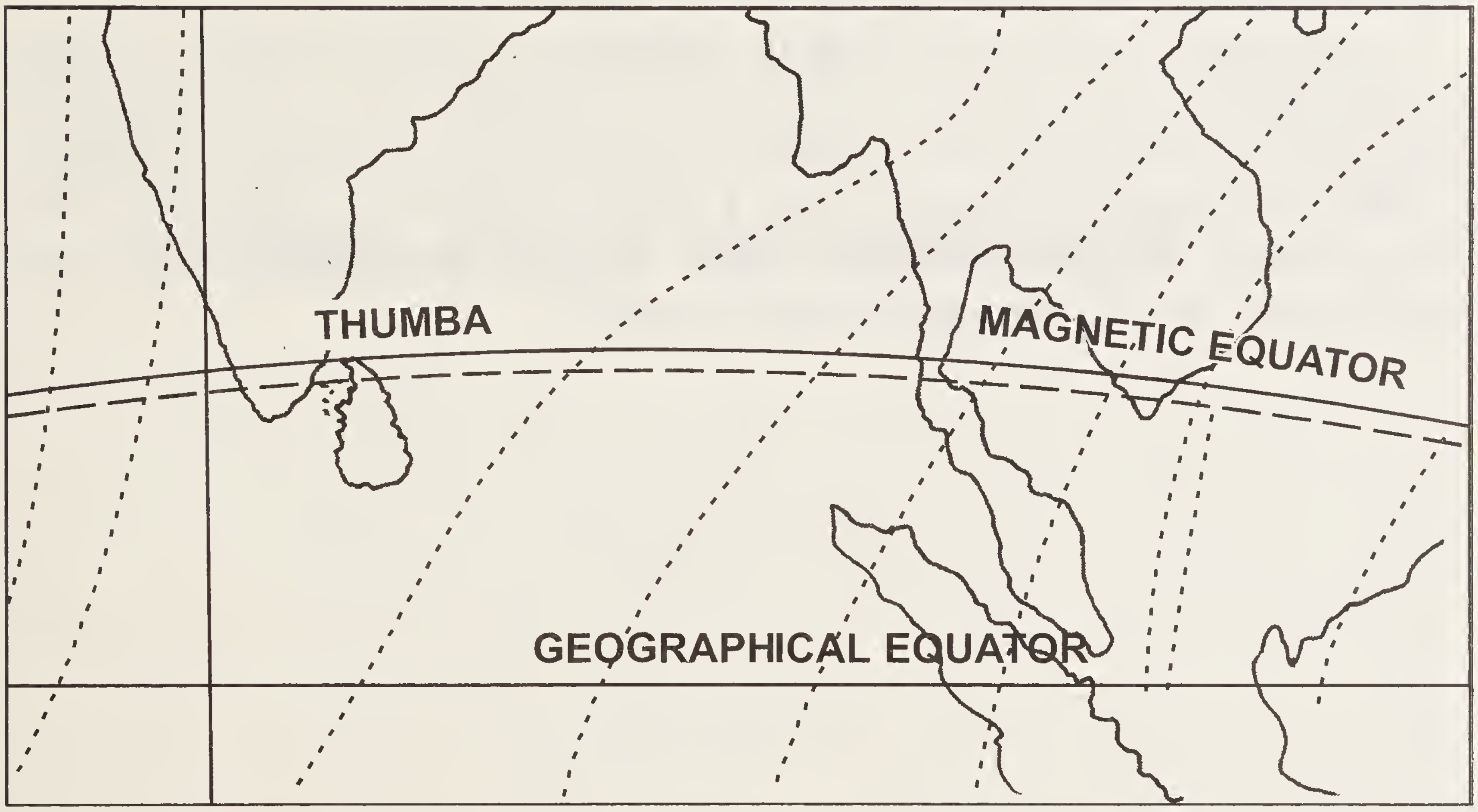


Fig. 1.1 : The magnetic equator: Thumba (located at 8° 32'34" north of the geographical equator and at 76° 51'32" E longitude) is less than a degree (0° 24N) away from the magnetic equator. The atmosphere above the magnetic equator is of special interest to scientists.

Rocket Parts on Bicycles

On 21 November 1963, four scientists arrived in Thumba, then an obscure fishing village, not well-connected to Thiruvananthapuram, with a hydraulic crane and parts of a Nike-Apache sounding rocket made in the U.S. Their mission was to assemble and launch the rocket. But the crane failed and started leaking. Undaunted, people pumped the hydraulic system and lifted the rocket on to the trolley and moved it away for a successful launch. Several similar missions, including India's own sounding rocket programme, followed.

When the Kerala government hesitated to give the land in Thumba for space research, Sarabhai approached Rev Fr Peter Bernard Pereira, Bishop of the area. Dr Kalam recalls it as a historic meeting where science and spirituality led

to a significant outcome. Fr Pereira, with the consent of his followers in the Church, conceded Sarabhai's request. The Church became a design centre where rocket parts were initially assembled. The Bishop's house was the working place for scientists.

Work on indigenous rockets was started in an old Church with the Bishop's house as the office. Some nose-cones were transported on bicycles as if marking India's transition from the Cycle Age to the Space Age! Sarabhai's enthusiasm was infectious. The dedication of the pioneers quickened the pace of work. A Space Science and Technology Centre was established in Thumba in 1965 (later named as Vikram Sarabhai Space Centre (VSSC). In Ahmedabad, a Satellite Communications Earth Station was set up in 1967.

Meanwhile, in 1965 the twentieth session of the United Nations accorded its sponsorship to the range in Thumba and recognised it as an international facility open to all members for launching sounding rockets for peaceful purposes. In 1968 the Thumba Equatorial Rocket Launching Station was dedicated to the United Nations. In 1969 the Indian Space Research Organisation (ISRO) was formed under the Department of Atomic Energy.

PART - II

THE PULL OF GRAVITY

3. Lift-off Into Space

The first layer of gas in the atmosphere called the troposphere, which extends up to about 16 km, offers the most resistance to a rocket (Fig 2.1). Here is the region where the weather is made, full of turbulence with winds and clouds. Even if a rocket does not go into orbit of the Earth, it has to overcome the atmospheric pull.

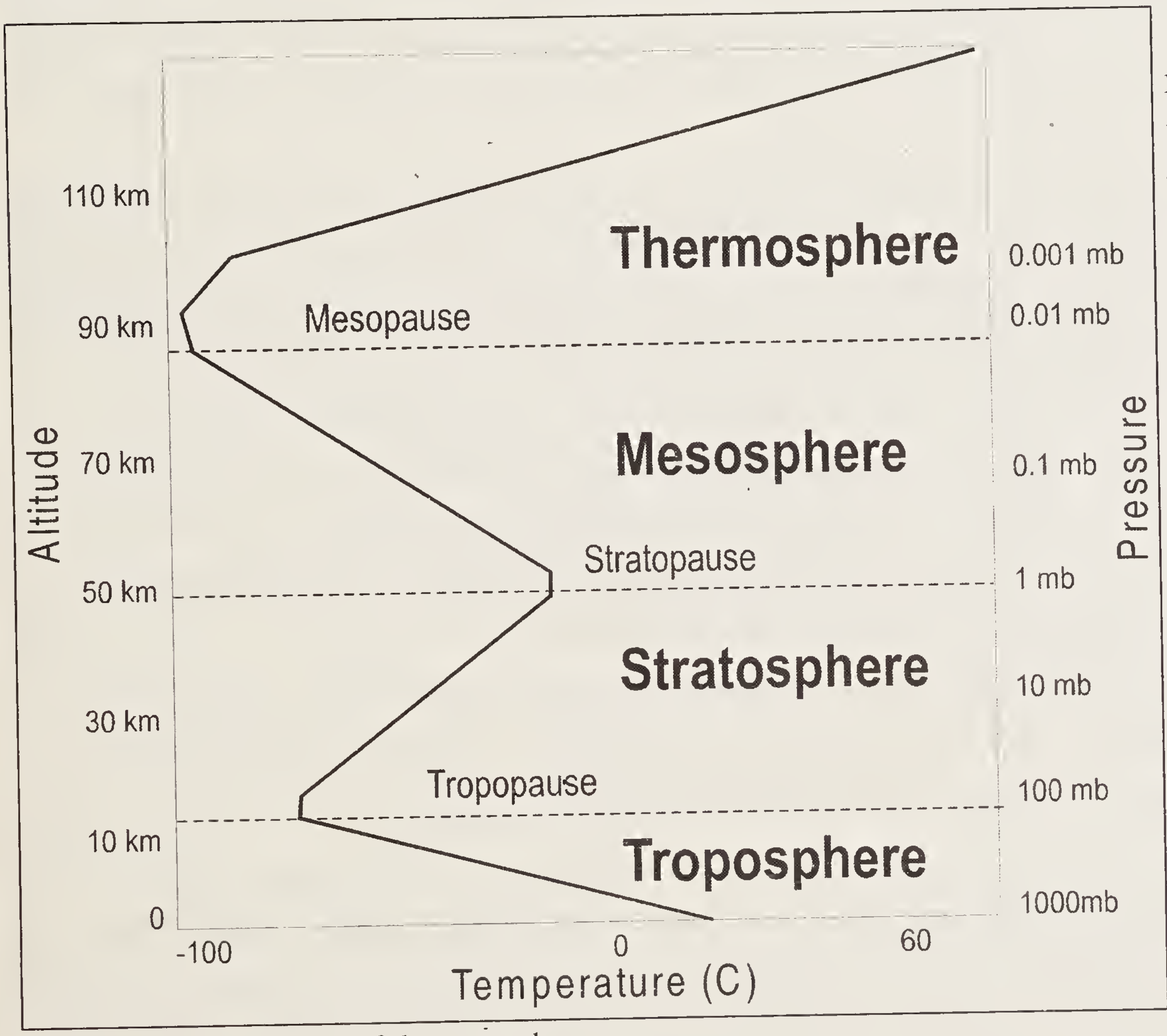


Fig 2.1 : Different layers of the atmosphere

A couple of years back, on October 4, 2004 to be precise, a rocket plane – called SpaceShipOne – was carried by an airplane to a height of 15 km before being boosted upwards. The rocket plane climbed to 114.64 km. The pilot Brian Binnie, took the weight of two others on board as required by the Ansari Prize of a million dollars, after repeating the feat a second time within a week. The limit reached by SpaceShipOne is just above 100 km, which is now regarded as the starting point where space begins.

Long before the airplanes were invented, Galileo had calculated the force that gravity exerts on a falling body at sea level as 980 cm a second, after every second, which is also referred to as one "g", a unit of acceleration. A rocket

has to overcome this force to go up, in addition to countering the atmospheric drag.

It was calculated that if the distance from the Earth is doubled, the pull of gravity comes down to only one-fourth of its force at the surface. If, for example, an object goes to a height of 6,378 km from the surface of the Earth, its distance from the centre of the Earth is doubled (as the equatorial radius of the Earth is 6,378 km) and the gravitational intensity becomes one-fourth of its initial force. There is, therefore, no need to spend at the initial stage all the force needed to push the rocket towards a given height. It would be enough if a part of the rocket is sent to some distance; the rest of the rocket could be propelled later on easily. This is the reason for having many stages in a rocket.

The use of iron for rocket cases and reasonably powerful propellants was first reported in the 18th century from Mysore, where its ruler had scored many a victory against the British with his rockets. The rockets neither had stages nor control. The British improvised on them.

Tipu's Rockets

"It was a great thrill to see an Indian innovation in a foreign soil well preserved and with facts not distorted." This is an observation of Dr Abdul Kalam in 1991, in his Hazrath Tipu Sultan Shaheed Memorial Lecture. The rocket scientist, who became India's President, was referring to his visit to the museum at Woolwich in England, which has carefully exhibited the rockets of Tipu, a former ruler of Mysore. The Museum displayed the caption to the rocket as follows:

The case is formed by a crude iron tube 7.8 inches long and 1.5 inches exterior diameter and is bound by strips of leather to a bamboo stick 6 feet 3 inches long.

A painting by Charles Hubbell, preserved by the Western Reserve Historical Society, Cleveland, Ohio, shows in graphic detail how the English troops and their horses were thrown up in mid air by the rockets, the first-ever in India, fired by the Mysore army led by Tipu Sultan. The fourth and the last Anglo-Mysore war in 1799 gave a bitter taste of the new weapon to the British, even though Tipu, betrayed by one of his commanders, was killed.

When some 700 rockets were taken to England along with bars of gold and other loot, the British lost no time in sending some of the rockets to the Royal Laboratory Woolwich Arsenal for analysis. Col William Congreve (1772-1828) of the Arsenal admitted within a year that the best of the British rockets were not half as powerful as those from

Mysore. He observed that the reason was the use of iron for the rocket case. He tried various combinations of propellants. Within five years, he was ready with a Congreve rocket. He was quick to recall that Newton's Third Law worked when the rocket was fired and pointed out that the rocket did not recoil when fired and so was ideally suited for ships.

The British took Congreve seriously and tried the rockets made by him to repulse the French at Boulogne. The rockets defeated Napoleon's navy and virtually ended his plans of crossing the English Channel. Later, the rockets were made in thousands and deployed in several wars in Europe and even in America.

If the British could preserve these objects of history, there is no reason why India should lag behind in preserving the sites associated with the first-ever Indian rockets. Places like the Tara Mandalpet in Srirangapatna near Mysore are in no way less important than Auburn, Massachusetts, where Robert Goddard launched the first liquid rocket from his aunt's cabbage garden. A fitting national memorial to mark the first-ever rockets in India would be appropriate.

The basic problems of reaching the orbit was solved in theory by a Russian school teacher, Konstantin E. Tsiolkovsky (1857-1935). He published his main results in 1903, the year of the Wright brothers' first airplane in Kitty Hawk. It was a rare coincidence. Tsiolkovsky held that only by a rocket with stages can one sufficiently overcome the pull of Earth gravity to go into space. Tsiolkovsky had pointed out that a single-stage rocket would need fuel four times the weight of the rocket and suggested multistages to meet the problem. The second and subsequent stages can take advantage of the speed already reached by the earlier stages. Besides the decreasing gravitational force, the air drag will become less and less.

A high velocity jet is generated by the combustion of a fuel and an oxidant. The atmosphere provides oxygen to an aircraft; but the present day rocket carries oxidant as well as fuel.

The thrust generated by a rocket is slightly higher in the vacuum of space than in the normal atmosphere, because the atmosphere reduces the thrust of a rocket. The thrust of the rocket (measured in pounds or kg) must be greater than the weight of the rocket at sea level. In other words, 10 tonnes of thrust will not lift a 10 tonne rocket off the ground. This is true of all rockets irrespective of their weight. Saturn V, for example, with the Apollo vehicle weighed 2,900 tonnes but the total thrust generated by its engines was 3,400 tonnes. The thrust-to-weight ratio will change, naturally, with the decrease in the

weight of the rocket, consumption of its fuel and decrease in the atmospheric pressure. Thrust can be increased, if the propellant is more efficient.

It was soon realised that rocket propulsion should be in accordance with Newton's Laws of Motion.

Newton's Laws of Motion

The tyres of a motor car push the vehicle against the road. In a rocket, the gases from it rush out to give it a forward thrust. Imagine a frog on a piece of wood floating on water. When a frog jumps off a plank, the wood is pushed in the opposite direction. The "frog" in the case of a rocket is the exhaust of the gases and the 'wood' is the rocket itself. Newton's Third Law of Motion states that for every action there is an equal and opposite reaction. The reaction or the thrust of the jet pushes the rocket in the opposite direction. Increased velocity results in increased momentum (which is simply mass into velocity) (Fig 2.2).

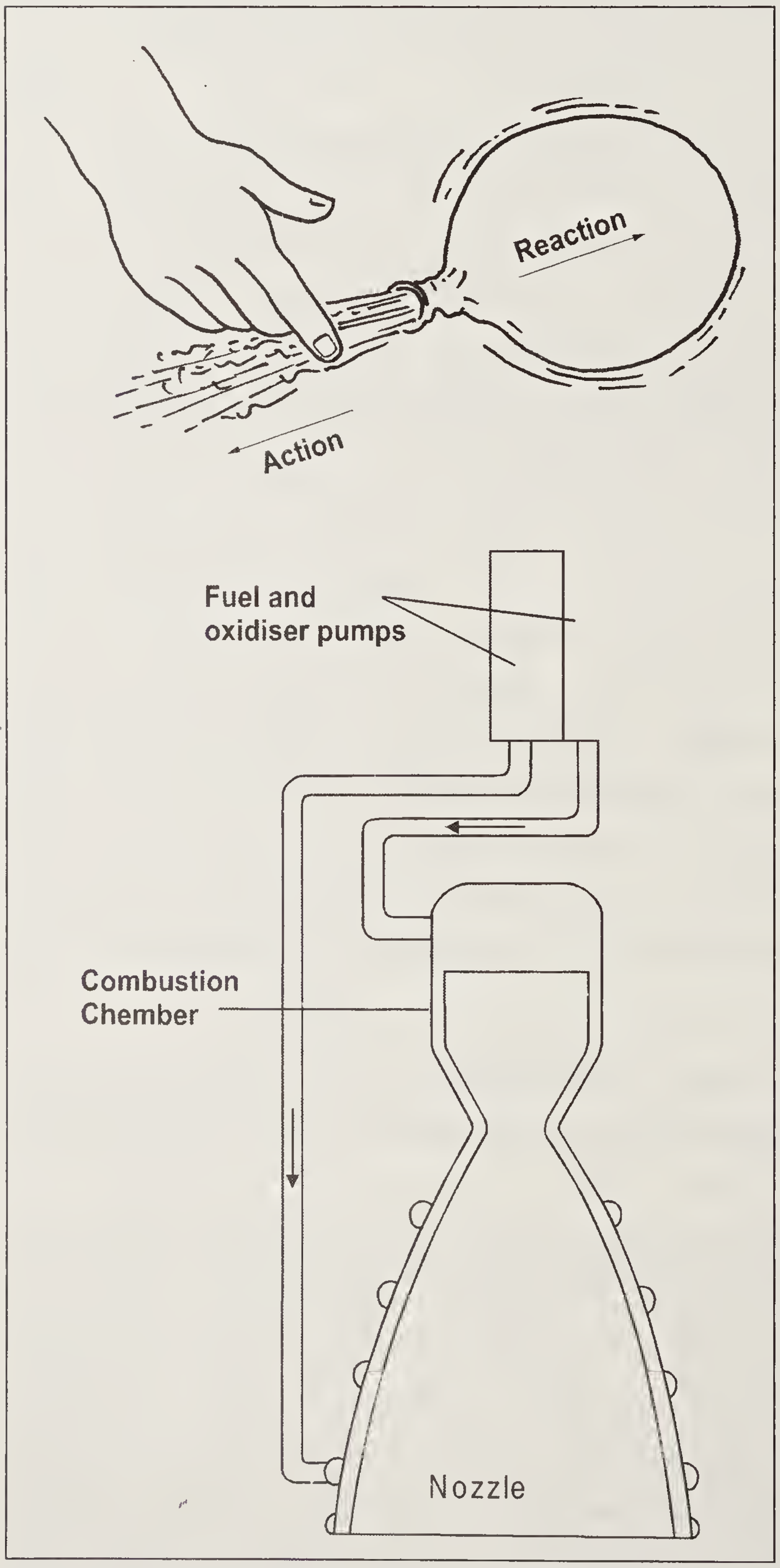


Fig 2.2 : Newton's Third Law of Motion provides the basic principle of rocket propulsion.

A rocket's control system is based on Newton's First Law, viz. a body remains at rest or in a state of motion in a straight line unless acted upon by an external force.

Newton's Second Law states that the rate of change of momentum is directly proportional to the force acting upon a body and indirectly proportional to the mass. Also, the force causes the body to accelerate in the direction of the force. From his laws, Newton calculated the gravitational force between the Earth and the Moon. The force, he said, is directly proportional to the product of the masses of the two bodies and inversely proportional to the square of the distance between them. He further

held that this law holds good everywhere and thus it was called the law of universal gravitation.

The Earth's gravity pulls down a falling body at about 980cm a second after every second at sea level. This force is described as one g. A rocket has to overcome this force. At 1.6 km a second, a rocket will reach a height of 130 km. If a rocket can inject a satellite at 7.91 or about 8 km a second, the satellite will go into a circular orbit of the Earth. If the velocity is 10.2 km/sec, the satellite will go into an elliptical orbit.

The force of a rocket, or the reaction experienced by its structure following the ejection of high velocity matter, is known as thrust. One way of expressing exhaust velocity is called specific impulse, expressed in seconds. It is an index of the rocket's performance, a ratio between thrust and fuel consumption. Specific impulse is the thrust derived from each pound of propellant in one second. Propellants made in India give over 242 seconds of specific impulse on ground, increasing to 270 seconds in vacuum.

The efficiency of a propellant is described in terms of its specific impulse, which is the impulse delivered per unit mass of propellant flow, measured in Newton-seconds. It measures the thrust derived from each pound of fuel in one second of engine operation. Greater specific impulse means more push from each unit of propellant. A specific impulse of 250 seconds means the propellant will produce 250 pounds of thrust at sea level for each pound of propellant burnt in one second. The significance of achieving higher specific impulse can be realised from a deceptively simple fact: every one second increase in specific impulse would enable the rocket to carry 10 kg of additional payload. The performance efficiency of a rocket depends on several other factors, including the shape of its nozzle.

Another fundamental feature of rocket flight concerns the enormous speed required. For example, to put a satellite into orbit, a rocket has to attain a velocity of 28,800 km an hour or 8 km (even 7.91) a second. A rocket has to attain a speed of 40,000 km/hr or 11.26 km a second, if it is designed to escape the Earth's gravity. This speed is known as escape velocity. It is not enough if the rocket reaches the speed at which its gases are expelled. It should fly faster than its own exhaust gases. Mathematically it has been shown that if the fuel-to-empty ratio (also called mass ratio, based on the total weight of the rocket to the weight that remains after all the fuel is exhausted) is 3:1, (2.72:1 to be precise), the rocket will go only as fast as its own jet of gases, provided there is no resistance and other drag factors. The German V-2 rocket, for example, had this ratio, with a total weight of about 15 tonnes and an empty weight of about 5 tonnes, though it did not attain the speed of its jet. Again, mathematically

it is proved that a rocket would go at twice the speed of its exhaust, if its mass ratio is 7:1. A higher mass ratio is possible, if the structure of a satellite is kept to the minimum giving way to maximum possible fuel. That is why the proportion of fuel in a rocket is more than the hardware, unlike in an automobile where the fuel accounts for a small percentage of the total weight. Rocket designers are therefore obliged to find light structures that would stand the force of nature.

4. A Sound Beginning

Scientists in India were aware of the fast developments in the Space Age, when they began their modest efforts on the shores of Thumba in the early 1960s.

Work began on designing and making an Indian sounding rocket. The first Indian rocket, launched on 20 November 1967, was typical of the pioneering effort. The rocket's diameter was 75 millimetres and it weighed only ten kg. It attained an altitude of 4.2 km. Some critics called it a toy. But Rohini-75 (RH-75), as it was named, proved the skill and confidence of the pioneers. As it zoomed away from Thumba, scientists compared notes and found that if the basic principles and techniques were correct, the size of the rocket would not be a big problem.

Bigger rockets were then being made in Trombay near Mumbai at the workshops of the Bhabha Atomic Research Centre. One of the rockets, known as Centaure, was manufactured under an agreement with France. The first three rockets of this type were made in Trombay. The manufacture of subsequent rockets was shifted to Thumba, where a Rocket Fabrication Facility was commissioned in 1971.

The diameter of the rockets increased within a short time. The Rohini series was called sounding rockets, which were useful for the study of the upper atmosphere. Such a rocket is launched almost vertically into the upper atmosphere and instruments on board transmit data on the surrounding environment. The Rohini series, developed and qualified by ISRO, include RH-125, RH-200, RH-300 and RH-560. The first two in the series are used for meteorological research, called Menaka rockets carrying a payload of about 5 kg. Menaka I is designed to carry its payload to a height of 55 km, while its improved version with two stages can take a payload to an altitude of 75 km. Centaure has a diameter of about 300 mm and can lift 50 kg of payload to an altitude of 160 km. Rohini-300 is similar to Centaure but has a different propellant. The single stage RH-300 can hurl a payload of 50 kg to 100 km, while another version of it can push the same weight to 150 km (Fig 2.3).

The launch weight of the rockets increased in five years from 60 kg to over 2 tonnes. The designs improved and controls became more and more

sophisticated. As the number and variety of the rocket systems increased, production methods were standardised. Though a rocket has hard material, its manufacture involves delicate craftsmanship to put together hundreds of its components. Even

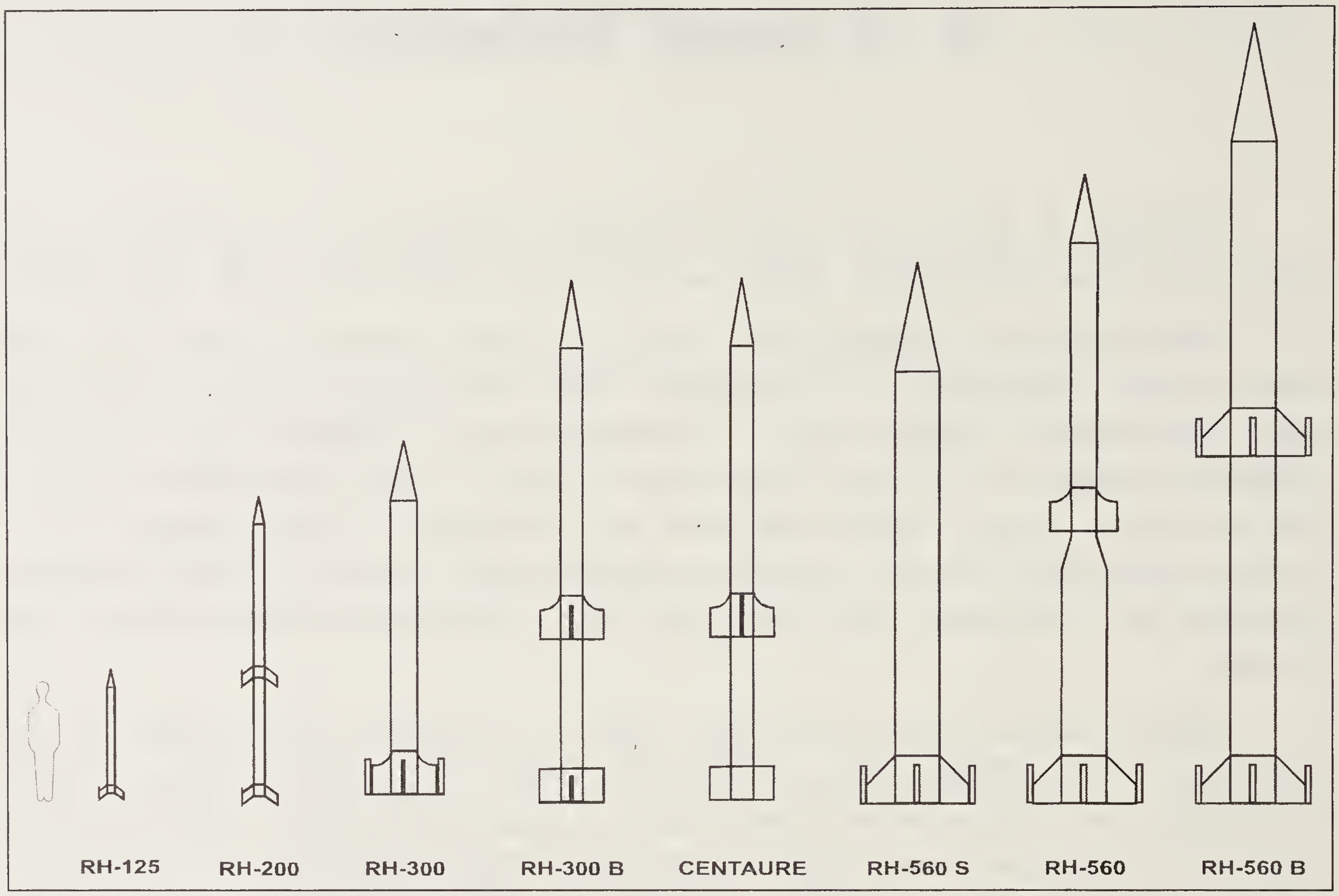


Fig 2.3 : Sounding rockets of ISRO: They are useful not only for scientific probes into the atmosphere but also as test vehicles for evaluating new technologies.

an RH-300 rocket has over 300 components ranging from latch pins to fins. Increased requirement of components called for uniform tools to make them. A master jig to make tools was installed for this purpose. The raw material needed special treatment. Steel sheets were given heat treatment. Welding was done with great precision when two stages were joined: the maximum deviation allowed was only 0.5 mm over a length of six metres. But for this precision, the rocket would not be stable in flight. Steel strips were wound helically or several layers of thin steel strips were bound together with resin.

The sounding rocket systems were used to develop and test several subsystems for advanced rockets and evaluate more energetic propellants. RH-125, for example, was used to study the separation of stages in flight and destruct system to be used in case of deviation from the planned course. In another innovation, three RH-125 rockets were clustered to serve as a big booster, while a fourth RH-125 was placed on their top as a sustainer. Tests were made to ensure that all the clustered rockets fired simultaneously. In order to stabilise the flight of a rocket through the dense layers of the atmosphere, fins and vanes

were provided. Fin tips interact with the flow of air around them, while jet vanes are placed in the nozzle to change the altitude of the rocket. The operation of the fins and vanes is controlled during the flight of the rocket. Payload recovery systems were tried from helicopter and balloons. It was first done with the help of French experts from Kourou. The payload was separated from the rocket at an altitude of 70 km. A parachute to stabilise it was deployed at a height of 8 km and main parachutes opened at 4 km. The descending payload was slowed down and recovered from the ocean with the help of a beacon transmitter and a dye-marker.

Another system developed was called deployable antenna for sounding rockets. The technique safeguards the antenna during its passage through the dense layers of the atmosphere. Yet another system was the ejection of the nose-cone. In some cases, the nose-cone was split into two halves. The process was so designed as to give minimum shock to the payload during the separation of the nose-cone. The technique gave the scientists valuable experience to undertake subsequently the separation of heat shields from rockets and satellites in advanced missions.

The programme of making sounding rockets continues, as they are useful for conducting various experiments. Rohini sounding rockets with 200 – 560 mm diameter can launch up to 200 kg payload to 300 – 400 km. Two Rohini – 560 M rockets with increased propellants will be joined together for testing scramjet propulsion. (see Chapter 8) Some sounding rockets are launched from Balasore on the east coast.

5. Sources of Energy

The old church in Thumba was the venue in the early sixties for studying advanced technical journals on rocket propellants. A small group of chemical engineers grasped the fundamentals in no time, but realising the ideas was another matter. It involved the design and development of numerous subsystems – all from the scratch. The know-how had to be developed indigenously; as being part of missile technology abroad, it was not available to the country.

The dream became a reality within five years. In 1969, a Centaur rocket with Indian propellant proved a shade better than its French original; the rocket soared 5 km higher than expected.

Propellant-making turned out to be a big challenge. A propellant supplies energy to the rocket, as petrol does to a car. But petrol is mixed with oxygen taken from the air to burn, while a rocket carries oxygen with it so that it can burn the propellant in vacuum. Air-breathing rockets (upto a certain height) have yet to be perfected.

A chemical rocket engine system is designed to generate thrust through combustion by releasing thermal energy derived from the chemical energy of the propellants. The high temperature and high-pressure products produced in the combustion chamber expand through the nozzle at high velocity imparting a momentum in the opposite direction to the rocket. The hot gases are obtained by burning either solid or liquid propellants or low temperature cryogenic propellants.

A propellant can be solid or liquid. ISRO started with solid propellants. Once ignited, a solid propellant cannot be switched off. A composite solid propellant consists of an oxidizer in a matrix of organic fuels (such as ammonium perchlorate in synthetic rubber). Based on the know-how developed by the Central Electrochemical Research Institute, Karaikudi, Tamil Nadu, the technology for making ammonium perchlorate directly from sodium chloride was perfected. The Ammonium Perchlorate Experimental Plant at Alwaye of the Vikram Sarabhai Space Centre (VSSC) meets all the demands of ISRO for propellant-grade oxidiser. Other products of the plant include strontium perchlorate, which is injected in the secondary vector control systems of bigger launch vehicles.

The fuel consisting of polyvinyl chloride is mixed with a binder such as carboxy terminated polybutadiene before the oxidizer is added. The propellants developed in Thubma, ranging from polysulphide and polyurethane to poly-butadiene represent the latest technology in the field. In energy content and mechanical properties, they come up to world standards. In fact, the solid propellants, used in the American Shuttle, are basically the same, consisting mainly of ammonium perchlorate as the oxidizer, powdered aluminium as the metallic fuel and poly-butadiene-based fuel-binder. As the propellants were developed, it was realised that many raw materials needed were just not available in the country. It was also recognised that it would not be enough to prove the new propellants in the laboratories. It was necessary to scale them up so that the country's industries could readily produce them. With the main objective of developing basic raw materials and proving the feasibility of using them in industry, ISRO set up a Propellant Fuel Complex at Thumba. The Complex makes a variety of chemicals including polymeric fuel binders for high-energy solid propellants.

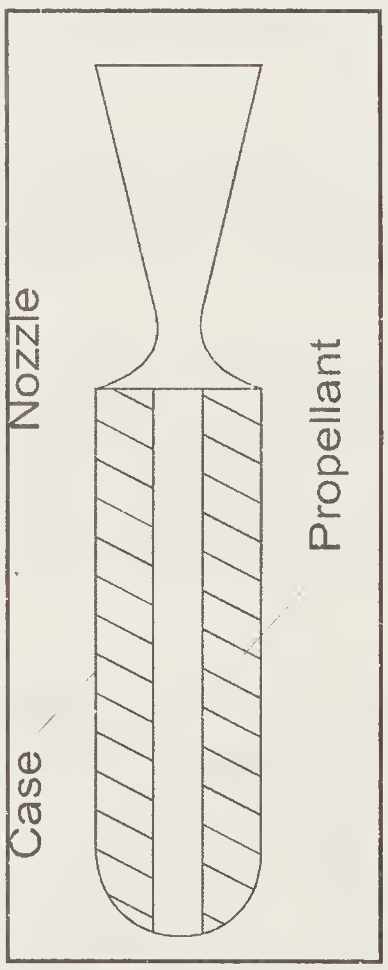


Fig 2.4 : Outline of a typical solid propellant rocket motor. The propellant grain is bonded to the case with a conical exhaust nozzle.

While the basic technology for making solid propellants was established in Thumba, it would have been risky to make bigger propellant segments there and transport them all the way to Sriharikota on the east coast for launch. It was therefore decided to make solid propellants on a big scale in Sriharikota itself. A solid propellant should burn all over the inner surface of the rocket from inside out. The chemicals should not explode, even though the temperature goes up to 3,000°C. If it does not burn steadily as required, the energy given will be substantially less (Fig 2.4).

Since the acquisition of the Centaure technology from France, considerable progress was made in the development of ISRO's solid propellant motors. The change-over to indigenous hydroxyl terminated polybutadiene (HTDB) propellant system required compatible mechanical properties for the strapons, core booster and the second stage motors. The third stage motor case was hardened to stand higher loads. The performance of the upper stage motors in ASLV was determined in the absence of validating high-altitude simulation tests. Propellant segments with varying burn rates were adopted to get the derived thrust of the strapon motors. Simultaneous casting of propellants reduced the variation in motor performance in the same launch vehicle. A significant aspect of these and other related developments has been the entirely indigenous effort in the design, development, assembly and testing of all the disciplines of the solid rocket

motor. Industries too were developed to acquire the capacity to produce critical raw materials, fabrication and other services.

Liquid Propellants

Liquid propellants are used in rocket motors that power various stages as well as in control motors. A monopropellant (e.g. hydrazine) has both fuel and oxidizer, and when passed through a catalyst, it decomposes at high temperature into constituent gases. A bipropellant consists of two unmixed chemicals (fuel and oxidizer) that are separately sent to a combustion chamber. Liquid propellants can be of two kinds, viz. storable and non-storable; the former can be kept at terrestrial environmental temperature, while the latter need to be cooled to render them liquid.

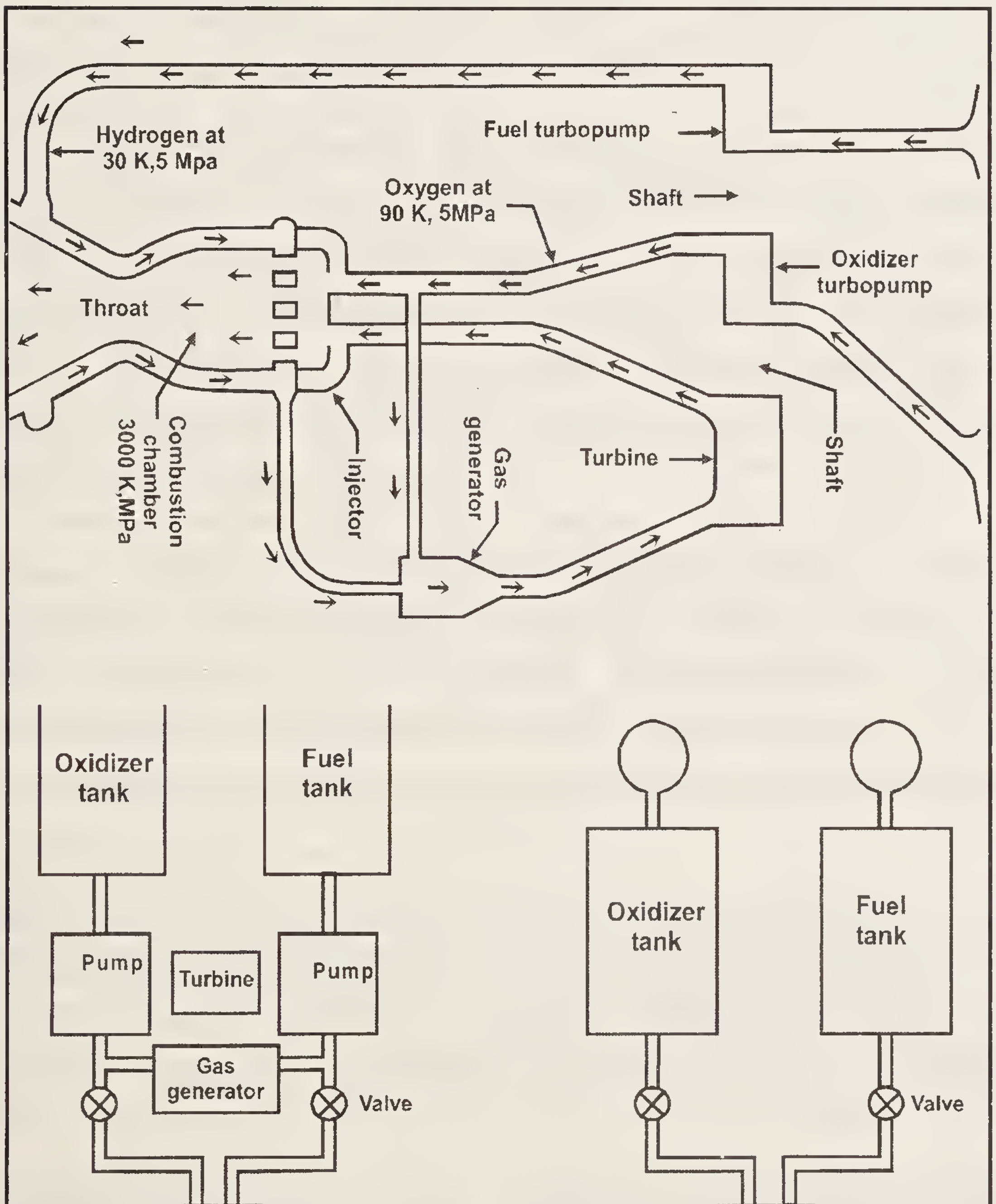


Fig 2.5 : Outline of liquid bipropellant rocket engines: pump-fed (top and left) and pressure-fed.

There are two types of liquid propulsion systems: pressure-fed and pump-fed. In the former, high-pressure gas (e.g. helium or nitrogen) pushes the fuel and the oxidant. In the latter, a turbine pumps the fuel and oxidant into the combustion chamber (Fig 2.5).

The four GSLV strapon stages as well as its second stage have pump-fed systems. They use unsymmetrical dimethyl hydrazine (UDMH) and nitrogen tetroxide (N2No4), which are storable propellants as they are stable over a reasonable range of temperature and pressure, unlike liquefied gases (liquid oxygen and liquid hydrogen) that have to be kept at very low temperatures (-183° C and –253° C, respectively) in the third stage (see chapter 16).

Propellant systems maximise the use of energy. It is common to use the fuel to cool the combustion chamber by sending the super cool fuel through tubes in the chamber and exhaust nozzle before entering the combustion chamber. The process is known as regenerative cooling. The absorption of heat from the engine increases the energy of the propellants. A crucial part of the propulsion system is the nozzle through which propellant gases are pushed out. A typical nozzle has a convergent section and a divergent exit cone, connected by a narrow throat. The throat is a critical area where the flow of gases changes from being subsonic to supersonic speed and is prone to damage. The degree to which the gases are expanded is indicated by the expansion ratio. It is the ratio of the widest area in the exit cone to that of the throat. The shape, size and strength of the nozzles affect the thrust. Different materials are selected for making them. At Thumba, the nozzles have been made from simple graphite and metal construction to more sophisticated designs. Lighter materials such as carbon and silica phenolic absortive liners are used. A gas jet facility to evaluate the liners has also been set up.

The first liquid rocket with a dummy payload was launched on May 15, 1973, while a similar combination was launched during night time a month later. Later a liquid second stage was combined with a bigger solid first stage of 560 mm, designed to produce a thrust of three tones. It was primarily a workhorse engine to enable the designers appreciate the nature of the components. The rocket was spun for stability but there were problems in handling the liquid fuel. A turbo-pump required for the liquid engine as well as a gas generator were designed. Full-scale efforts to develop liquid motors were soon started, once it was decided to introduce liquid propellant stages in the polar satellite launch vehicle. Meanwhile, several liquid propellants including unsymmetrical dimethyl hydrazine (UDMH) and nitrogen tetroxide were developed. The know-how for making UDMH was given to the Indian Drugs and Pharmaceuticals Limited for production, while the production of nitrogen tetroxide was entrusted to the Hindustan Organic Chemicals.

Liquid engines pose some peculiar problem, including what is known as slosh and pogo problems. The slosh is caused by the motion of the liquids in containers, resulting in interference with autopilot functions. The pogo problem arises because of the interaction of the propulsion system with the structural dynamics of the propellant feed lines.

Solid and liquid propellants have their advantages as well as disadvantages. Solid motors are simpler but cannot be switched off and on. Liquid motors provide enhanced power and can be controlled but need complex mechanisms to operate them. There is a trade-off and the choice depends on the specific mission. It is common to use both solid and liquid propellant motors in the same rocket (e.g. PSLV).

6. Launching from Sriharikota

While Thumba was used for launching sounding rockets, bigger rockets called for a launching centre on the east coast to take advantage of the safety of the sea during a rocket launch. Satellites launched eastward from near the equator can take maximum advantage of the Earth's eastern spin. After a search, Sriharikota, an island close to the country's eastern coast, about a hundred kilometres north of Chennai, was chosen. With the Bay of Bengal on its eastern side, the island is about 7 km wide and has a coastline of 44 km. The island is separated from the mainland by the Pulicat lake. On the western side of the land adjoining the island are the famous Tirumala Hills. The spindle-shaped island is 17 km from its nearest town, Sullurpeta, on the Chennai-Kolkata rail line in Andhra Pradesh. The island, rich in forests, is a haven for migratory birds from the North during winter.

As the early visitors traced their way from the seashore to the forest, they were surprised to find amazing skills displayed by the Yanadi tribe of the area. The Yanadi boys could "read" the footprints on the sand and correctly guess whether their elders had walked that way.

Geographically, Sriharikota is located at 80° East longitude and 13.6° North latitude. Being near the equator, it has a natural advantage. The Earth's rotational velocity there is 1613 kmh, which would give an additional push to a rocket launched eastward. Heavy rains lash the island from October to December. The Sriharikota Range (SHAR) was established in 1969 for launching India's satellites. SHAR today is an important launch centre in the world with modern facilities for launching satellites into polar and near-Earth orbits. SHAR is now known as the Satish Dhawan Space Centre in memory of Prof. Dhawan, who played a key role in developing the Centre and other missions of ISRO.

SHAR became operational on October 9, 1971, when Rohini-125, a small sounding rocket, was launched. Numerous facilities have since been added to meet the growing needs of ISRO. Today, SHAR has a solid propellant plant, a rocket motor static test complex, launch complexes for a variety of rockets, telemetry, telecommand, tracking and data acquisition facilities besides other support services.

A major facility is called SPROB, acronym for Solid Propellant Space Booster Plant. The Yanadi boys are able to pronounce it correctly!. It processes solid propellant motors upto 2.8 m in diameter. The propellant consists of ammonium perchlorate as the oxidizer and HTPB as the fuel with aluminium powder as an additive. The static facilities can test the motors both at ambient and simulated high-altitude conditions.

The complex has a mobile service tower, based on a steel structure 76.5 m tall, weighing 3,200 tonnes. When the launch vehicle is fully integrated, the service tower is moved to a distance of 180 metres. An umbilical tower (52 m) is connected to the launch vehicle at various levels for supplying propellants, cooled air for satellite and equipment bay (until lift-off) and electrical power for check-out.

Rocket motors are checked at the integration facilities. The liquid propellants, kept in storage tanks, are transferred on commands given from a control room 200 m away. The second and fourth stages of a PSLV, for instance, are filled during a 72-hr countdown. A gas storage facility near the launch pad has high-pressure nitrogen and helium gas, which are supplied to the umbilical tower. Eye/face wash and emergency showers are installed at all propellant-handling installations. Two check-out facilities have been established, one near the launch pad and the other at the launch control centre away from the launch pad. There is an automatic launch processing system activated. for example, in the last 10 minutes before lift-off of a PSLV.

A satellite integration facility has three sections: one, functional tests on subsystems, and compatibility with ground stations through radio etc.; the second, mainly for filling the reaction control system and air for propellant charging operations; and the third, for satellite assembly and integration with the launch vehicle. The integration, check-out and launch operations are monitored through closed-circuit TV system. High-speed cameras are also used. The Mission Control Centre co-ordinates operations during launch vehicle integration and check-out, monitors launch operations, subsystems, ground systems for supporting the launch operation, conducts simulation exercises and authorises the launch.

The data from all ground stations, vehicle and the satellite are displayed at the Mission Control Centre. Two computer systems are pressed into service to process the data. Weather information, including the data from satellites, is displayed. All key persons take their positions at the control centre during the countdown. Real-time monitoring of the performance of the launch vehicle is done with the help of a computer. Quick-look flight data and confirmation of flight events are also provided.

SHAR is the principal ground station, providing facilities for receiving telemetry data from rockets and satellites, for sending telecommands to them and for

tracking them. Telemetry consists of receiving telemetered data from a rocket or satellite on the performance of its various systems. Various parameters such as pressure, thrust or temperature are sensed by onboard electronic gadgets and the data are transmitted at given frequencies to ground stations. A powerful antenna automatically tracks the onboard transmitter. The data are also transmitted to computers in real time for processing and display.

The tracking network in SHAR has three high-precision and two medium precision C-band radars (4-8 GHz) besides one operating in S-band (around 2 GHz). One of the C-band radars can track a transponder of 400W peak power upto 3200 km. The transponder responds automatically when signalled from the ground.

Tone ranging measures the distance of an object from the ground. Different tones (electrical signals) are sent from a ground station to a rocket or a satellite and are retransmitted back. The time delay in getting the signal back is proportional to the line-of-sight distance between the station and the object. Another system, interferometry, is used to know the angle of a rocket or satellite correct to 0.1° in elevation. The velocity of the satellite can also be measured from the ground. Just as a shrill whistle of a passing train fades as it crosses a stationary onlooker, the frequency of the signals from a passing satellite changes apparently depending on its speed. By measuring the change (known as the Doppler shift), the velocity of a satellite is computed.

When a vehicle is in flight, more than one tracking system is operated to provide redundant capability. The tracking data are transmitted to computers in real time. The trajectory is displayed in the range safety room.

The telecommand system is used during the launch phase for range safety. In case the vehicle deviates beyond allowed limits, it can be destroyed on command from the range safety officer.

A powerful transmitter and associated system are used for the purpose. During on-orbit operations, telecommands are used to manoeuvre the satellite so as to maintain its position accurately and carry out other instructions.

The support systems include a master timing station, which generates universal time codes and transmits time signals. An extensive communication link is set up for teleconferences. Radio links are used to get clearance from the air and sea traffic control authorities in Chennai. A four-channel closed-circuit television, a meteorological tower and photographic facilities with high-speed cameras have also been provided.

During the pass of a satellite, data received are displayed selectively for a quick look in real time. This would mainly enable the controllers to assess the health of the satellite. In near real time, the trend of the behaviour of subsystems

can be studied. For example, the temperature rise, voltage discharge and similar developments can be observed. After the initial post-launch period, monitoring and command are carried out in Bangalore.

The Second Launch Pad

The second launch pad at SHAR was dedicated to the nation by President Kalam in 2005. It was from SHAR that SLV-3 (of which Dr Kalam was Project Director) launched a 40 kg Rohini satellite into orbit, as against a 1600 kg satellite launched by PSLV-6 (2005) into polar sunsynchronous orbit. Today, a 4,000 kg satellite can be launched into the low Earth orbit.

The second launch pad would enable ISRO to launch four satellites in a year. The launch pad has been secured against a wind speed of 30 m per second by an anchoring system, developed for the purpose. A mobile launch pedestal to transport the vehicle to the pad was designed and fabricated. The lightning and rain-proof systems have also been set up.

PART - III

ORBITS

7. The Geosynchronous Orbit

Few ideas change the course of history. An idea that has made satellites part and parcel of our daily life is the geosynchronous orbit. Actually, it was proposed in 1945, long before the Space Age. The famous science writer, Arthur C. Clarke, outlined the idea in a magazine, which envisaged relay of radio signals from a satellite around the Earth. The orbit is one of the best gifts of Nature; its use has changed the world for ever in terms of communication and entertainment. The idea could be realised only in the Space Age. Today, both elliptical and circular orbits are useful to place satellites (Fig 3.1).

The orbital period of a satellite in the geocynchronous orbit is almost equal to the period of the Earth's daily rotation (viz. 23 hours 56 minutes 4 seconds or the period of a sidereal day measured with respect to distant stars, instead of the Sun). A satellite in such a position will appear to be stationary with respect to the Earth; hence it is called a geostationary or geosynchronous satellite. A satellite in GEO will have to orbit at a velocity of 11,068 km/hr at about 35,900 km above the equator in order to synchronise with the speed of the Earth's rotation on its axis (viz. 1,620 km/hr). Moreover, the satellite should orbit from west to east, as does the Earth, and the plane of its orbit should coincide with the equatorial plane of the Earth (with zero degree inclination). At a distance of about 36,000 km, three satellites, placed 120 degrees apart, can 'see' the entire Earth.

A practical use of an Earth orbit was suggested by a Boston clergyman, Edward Everett Hale. His was the first-ever suggestion of an artificial satellite in orbit. He wrote in the *Atlantic Monthly* in 1870 that such a satellite would be useful for navigators at sea. But it remained buried in technical literature.

The first American orbital effort in December 1957 failed miserably. It was only after Sputnik-1 went into orbit that the German-born rocket expert, settled in the U.S., Warnher Von Braun (1912-1977) was given the challenging task of placing a satellite into orbit within 90 days. He did it in 84 days, based on his previous work. And Explorer-1, America's first satellite, was in orbit in 1958.

The U.S. tried Moon probes in the first year of the Space Age but failed. The initial Russian lunar attempt also failed, as their satellite went into an orbit

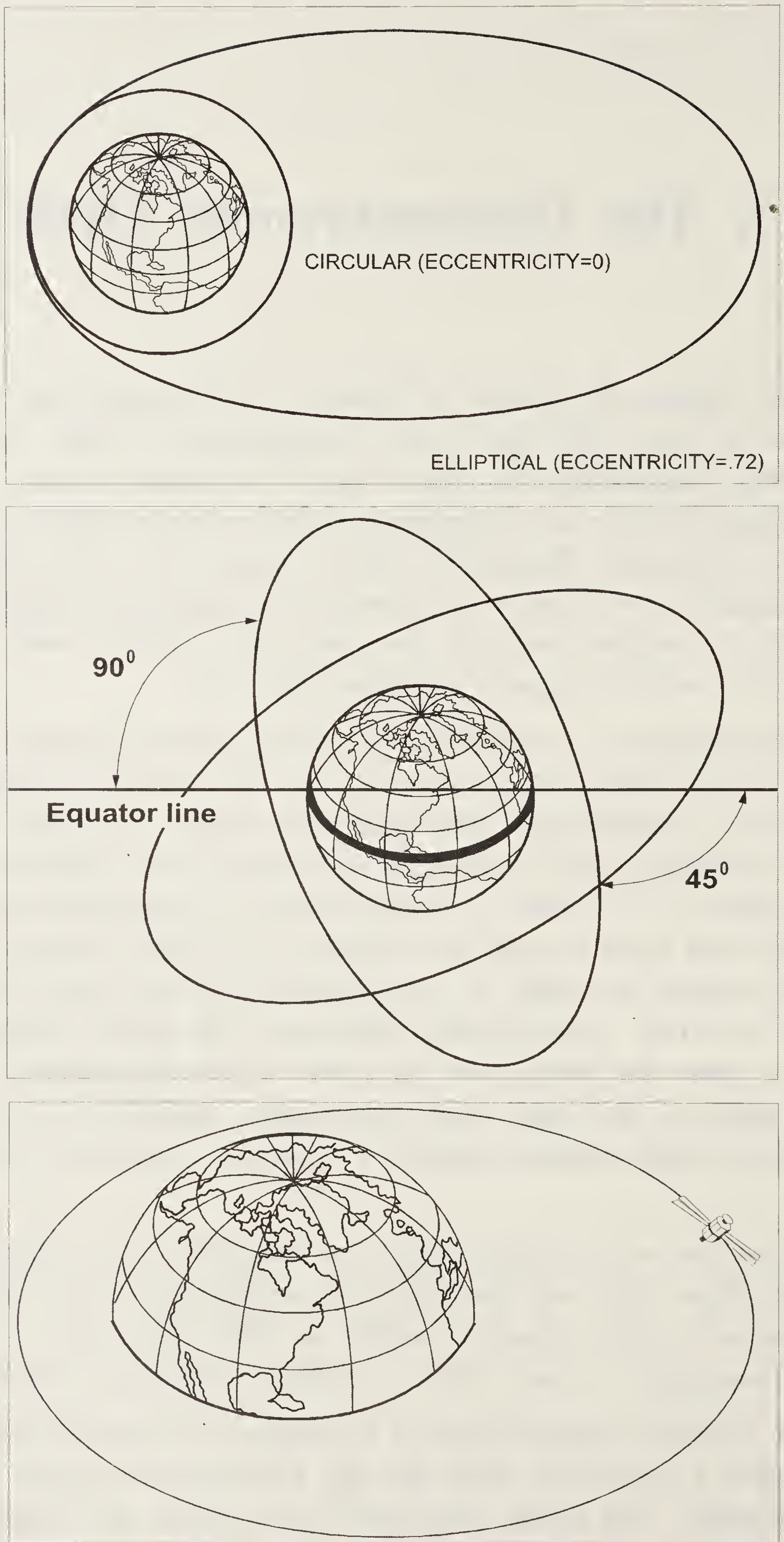


Fig 3.1 : The degree to which an orbit is elliptical is called its eccentricity. A circular orbit should have zero eccentricity. However, due to Earth's gravity, no orbit is truly circular! A highly elliptical orbit may have, for example, an eccentricity of point 72. The tilt of the orbit with reference to the equator is called inclination. An equatorial orbit will have an inclination of zero degree. Low Earth orbits can have, for example, an inclination of 90 or 60 degrees.

around the Sun! Meanwhile, US engineers tried to put communication satellites into orbit. The National Aeronautics and Space Administration tried the first communication satellite, ECHO-1 in 1960. In July 1962, Telstar 1 made the first transatlantic TV transmission, though the geosynchronous orbit was not perfect.

Satellites launched towards the east can take advantage of the Earth's eastward rotation, mostly at the equator. It has been found that the most efficient way of going into the GEO is to first attain a lower Earth orbit called geostationary transfer orbit (GTO). The GTO is an egg-shaped orbit, made circular on the basis of a principle first elaborated in 1925 by a German physicist, Walter Hohmann (1880-1945) to describe a unique trajectory between the orbits of planets. Based on this principle, the trajectory that connects two circular orbits in such a way that it is tangential to both, needs minimum velocity change and hence minimum propellant (Fig 3.2).

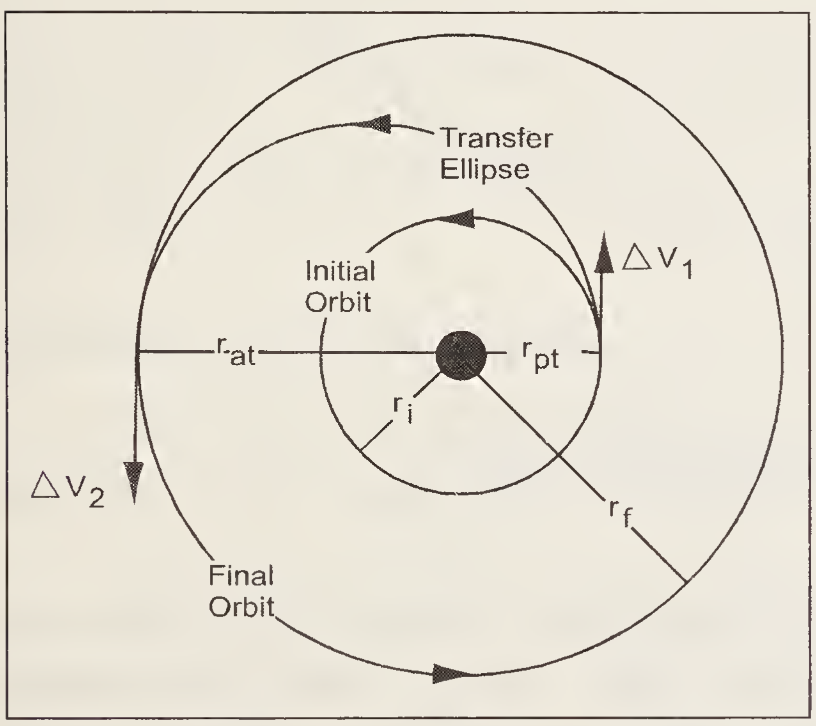


Fig 3.2 : The Hohmann Transfer in which a satellite in an elliptical transfer orbit, when it is tangential to the initial and final orbits, can go into the final circular orbit in an energy-efficient manner.

Accordingly, a satellite is put into a transfer orbit with a perigee (nearest point) of about 250 km from the Earth and an apogee (farthest point) of about 35,900 km. An apogee rocket, fixed to the satellite, is fired to transfer the satellite from one orbit to the other. For example, INSAT-4B (2007) was in an initial orbit of 243 km (perigee) by 35,876 km (apogee) at an inclination of 4.5° to the equator. ISRO's Master Control Facility took charge and raised the orbit in two manoeuvres (by timing the onboard liquid apogee motor) to 32,878 km by 35,736 km, and reduced the inclination to 0.19°, the third and final manoeuvre to near geosynchronous orbit (Fig 3.3).

There is often a mistaken impression that the speed of the satellite in GSO and that of the Earth on its axis are the same. It is not. The two speeds synchronise. The speed of the satellite at the egg-shaped orbit is typically 10.15km/sec at the perigee, while it is 1.61 km/sec at the apogee. Hence it would need only an addition of 1.46 km/sec to attain the speed of 3.07 km/sec in the circular geosynchronous orbit. The liquid apogee motor (LAM) on board the satellite contributes nearly half the velocity of the satellite in GSO. In the three firings consumes two-thirds of the total liquid propellants. The balance is considered adequate to operate the small rockets on board the satellite to keep it stable over its designed lifetime of 12 years.

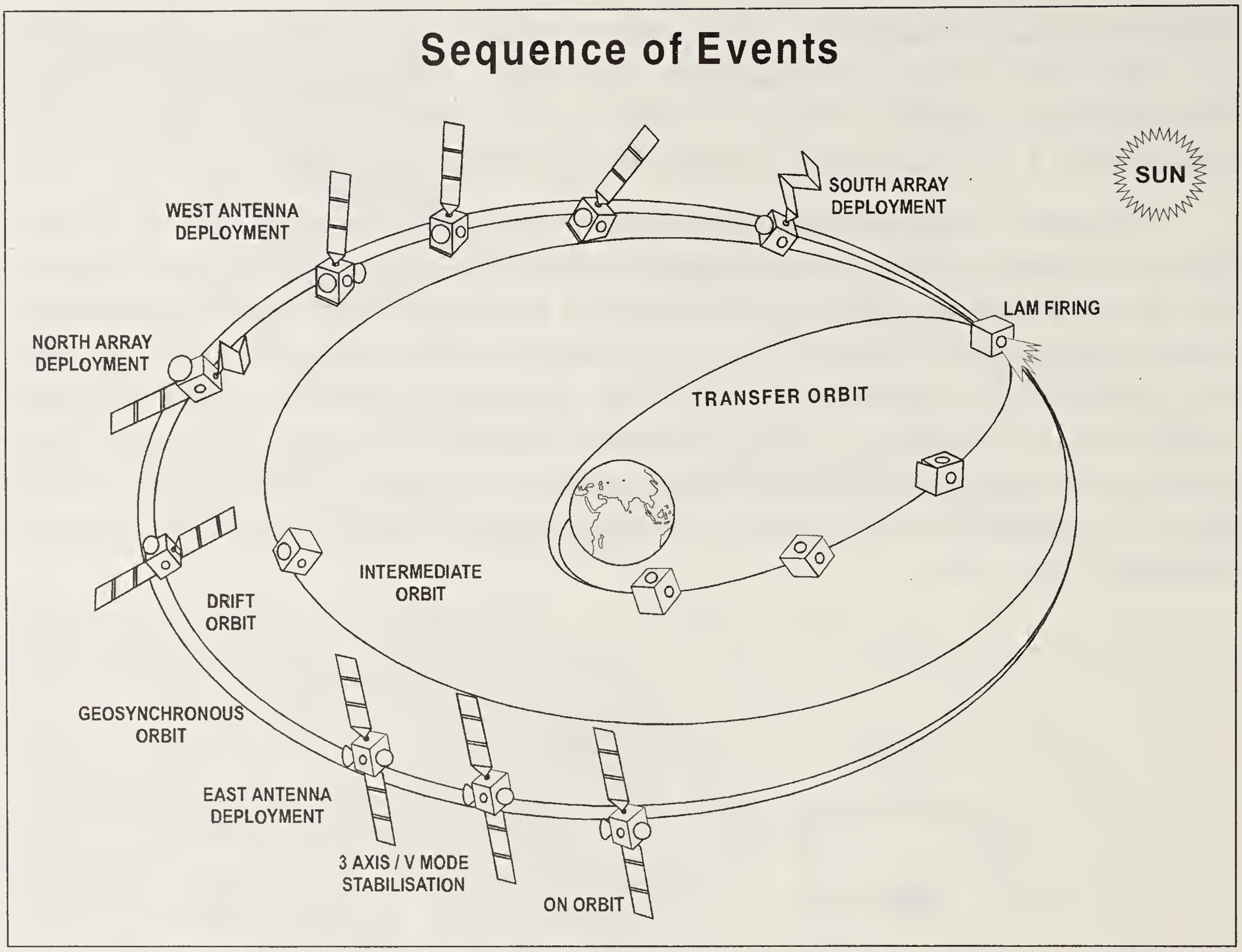


Fig 3.3 : Mission sequence (INSAT 3E) from launch to geosynchronous orbit

In and Out of the Earth's Shadow

The Earth's spin axis and hence the geostationary orbital plane is inclined at 23.5° to the ecliptic, the plane containing the Earth and the Sun. But for this, the satellite would be eclipsed by the Earth every day. In fact, satellites in low Earth orbits (lasting 90 minutes) are in the Earth's shadow for about 35 minutes. But the entire geostationary orbit is sunlit for most of the year (Fig 3.4).

At the winter and summer solstices, for example, the satellite is either above or below the ecliptic and thus avoids the Earth's shadow, while at equinoxes, it crosses the ecliptic into the Earth's shadow. At about 22 days before the spring equinox, the satellite gets into the shadow and spends longer and longer periods (starting with 10 minutes) in the shadow until it reaches the maximum at equinox, when the eclipse period is 72 minutes a day. This period decreases as the satellite travels towards the end of the eclipse season (22 days later). The pattern is repeated in reverse around the autumn equinox. During the eclipse period, onboard batteries supply power to the spacecraft. Twice a year, the Sun is located exactly in the direction of the Earth station antenna beam, affecting the communication link for about 23 minutes. These occasions are, however, predictable. As a

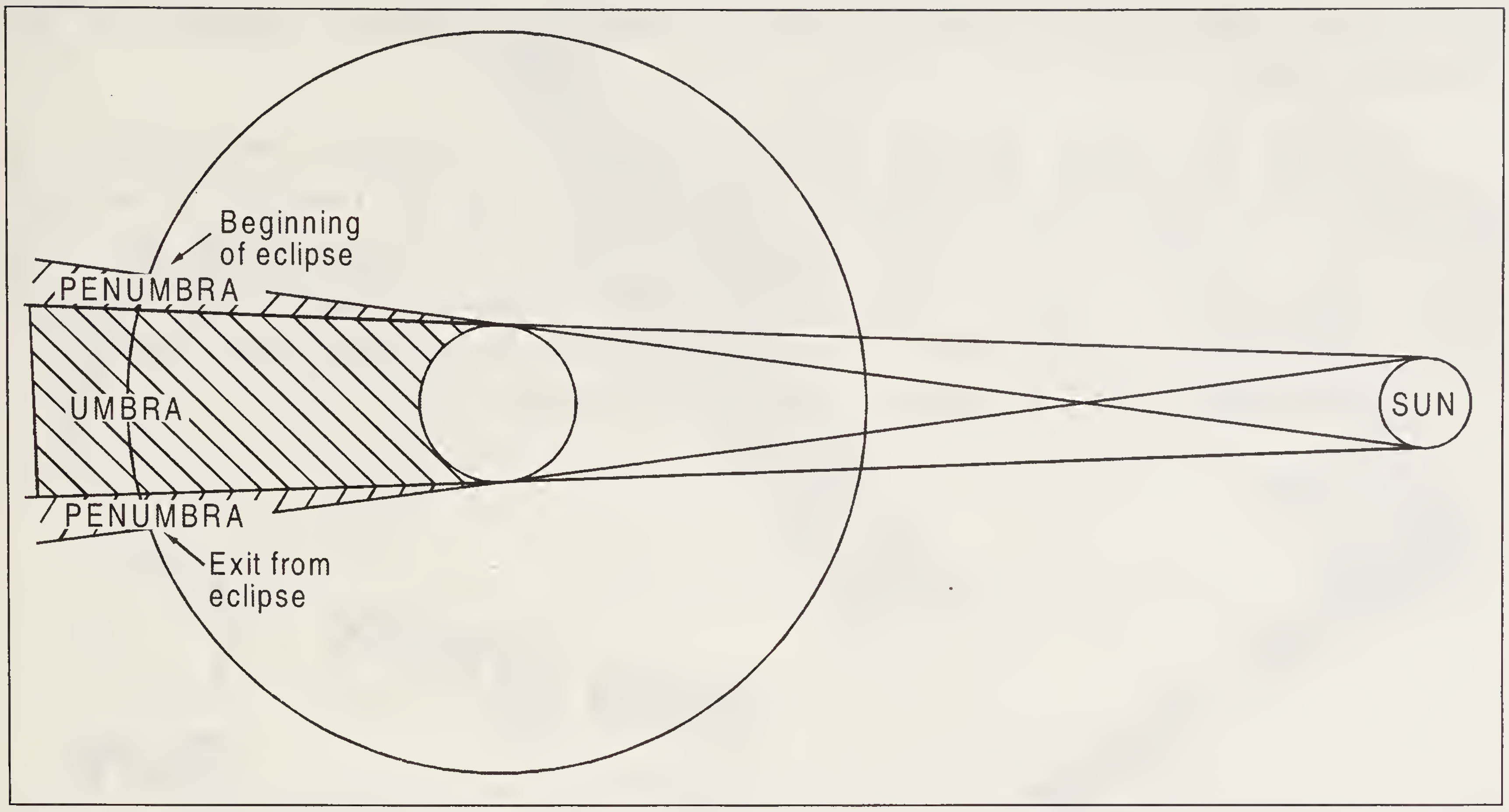


Fig 3.4 : Twice a year, a geosynchronous satellite goes into an 'eclipse' of the Sun, when onboard batteries supply power.

precaution, one of the Earth sensors is switched off to avoid being blinded by the Sun!

Attitude and Orbit Control

Reaching the GEO is, however, the first step. Staying there in a stable condition is an equally big challenge.

Someone compared the placing of a satellite in orbit to a marriage! Just as a life-long period of adjustment begins after the successful ceremony, the satellite too needs constant observation and action to take care of deviations. If the satellite were not placed at the correct distance (about 36,000 km), its orbit would have been more or less than 24 hours and so would not be constantly visible as a fixed star in the same place from its footprint area. The location of the satellite is therefore kept within plus or minus 0.1°. In the north-south direction, the deviations are corrected once in 60 to 100 days, while in the east-west direction, it is done once every three days. The small rockets for correction would be used in co-ordination with other stabilising devices such as momentum wheels and reaction wheels on board the satellites.

A spacecraft's orbit is perturbed mainly by three phenomena: the Earth's shape, lunar-solar gravity and the solar wind. First, the bulging of the Earth's equator and a flattening of the poles have resulted in a polar radius, which is some 21 km shorter than the average equatorial radius. The equatorial radius varies, the difference between the minimum and maximum radii being about 70 metres. This difference, leading to the equator's ellipticity, detected through its

gravitational effect on the orbital paths of satellites, affects a satellite in the equatorial orbit.

Second, the Moon and the Sun contribute to a satellite's perturbance. A satellite in the equatorial orbit tends to rise and fall with the tides in the oceans. The Moon's gravitational pull on a spacecraft varies constantly. Third, the solar wind – the steady stream of charged particles from the Sun – can disrupt satellites by its continued effect on the solar panels in the long run. Moreover, sudden solar flares can completely disrupt the satellites (Fig 3.5).

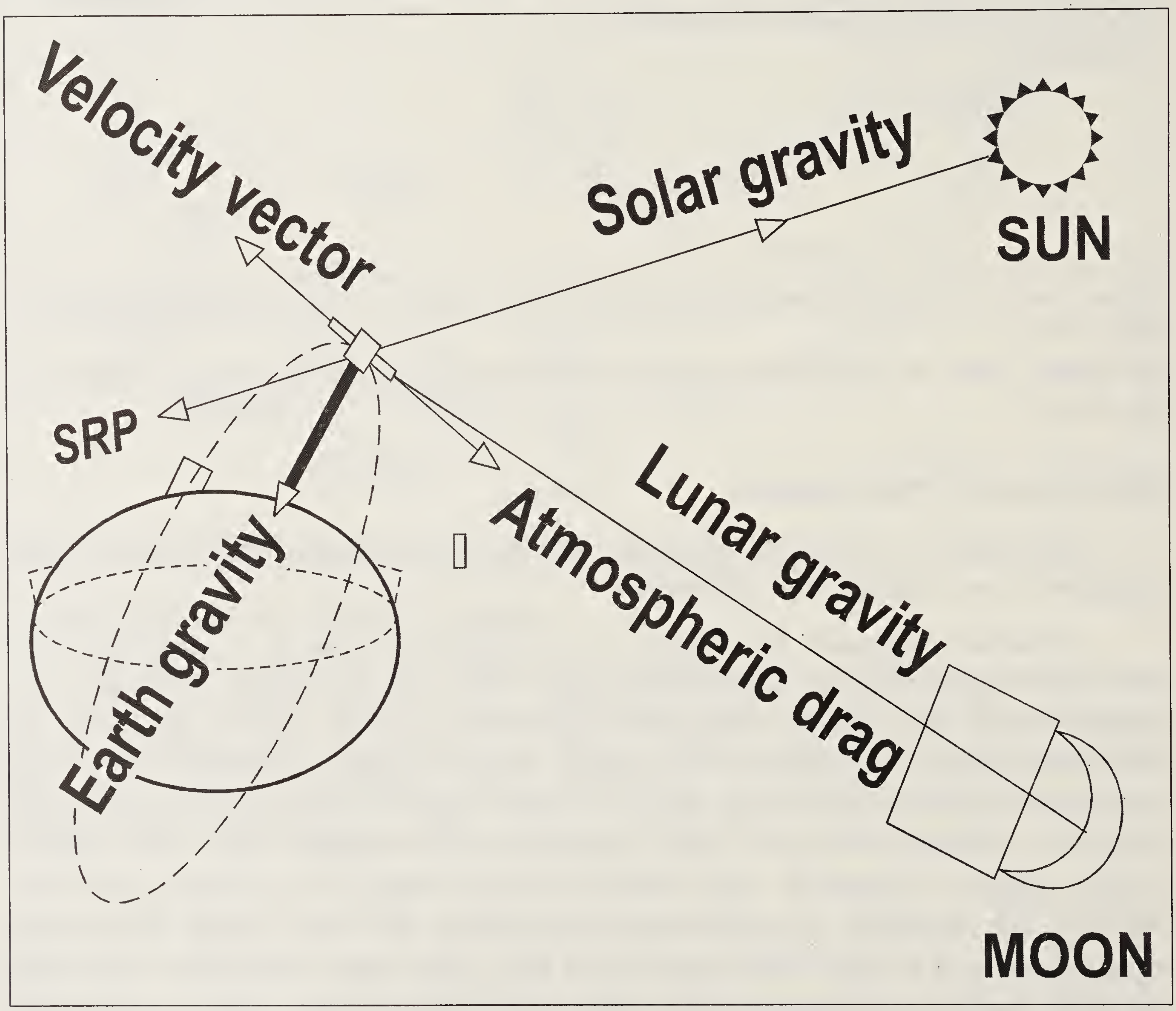


Fig 3.5 : The Sun, Earth and its Moon as well as the Earth's atmosphere exert pressure on a satellite in orbit. Constant adjustments are necessary to keep the satellite rock-steady in the allotted slot.

A drum-shaped satellite can be steady by spinning at a constant rate, while the satellite's antennas are kept pointed at the Earth. Alternatively, a box-shaped satellite can have three-axis stabilisation. The three axes are: the roll axis that maintains the satellite along the direction of its motion, the pitch axis that steadies

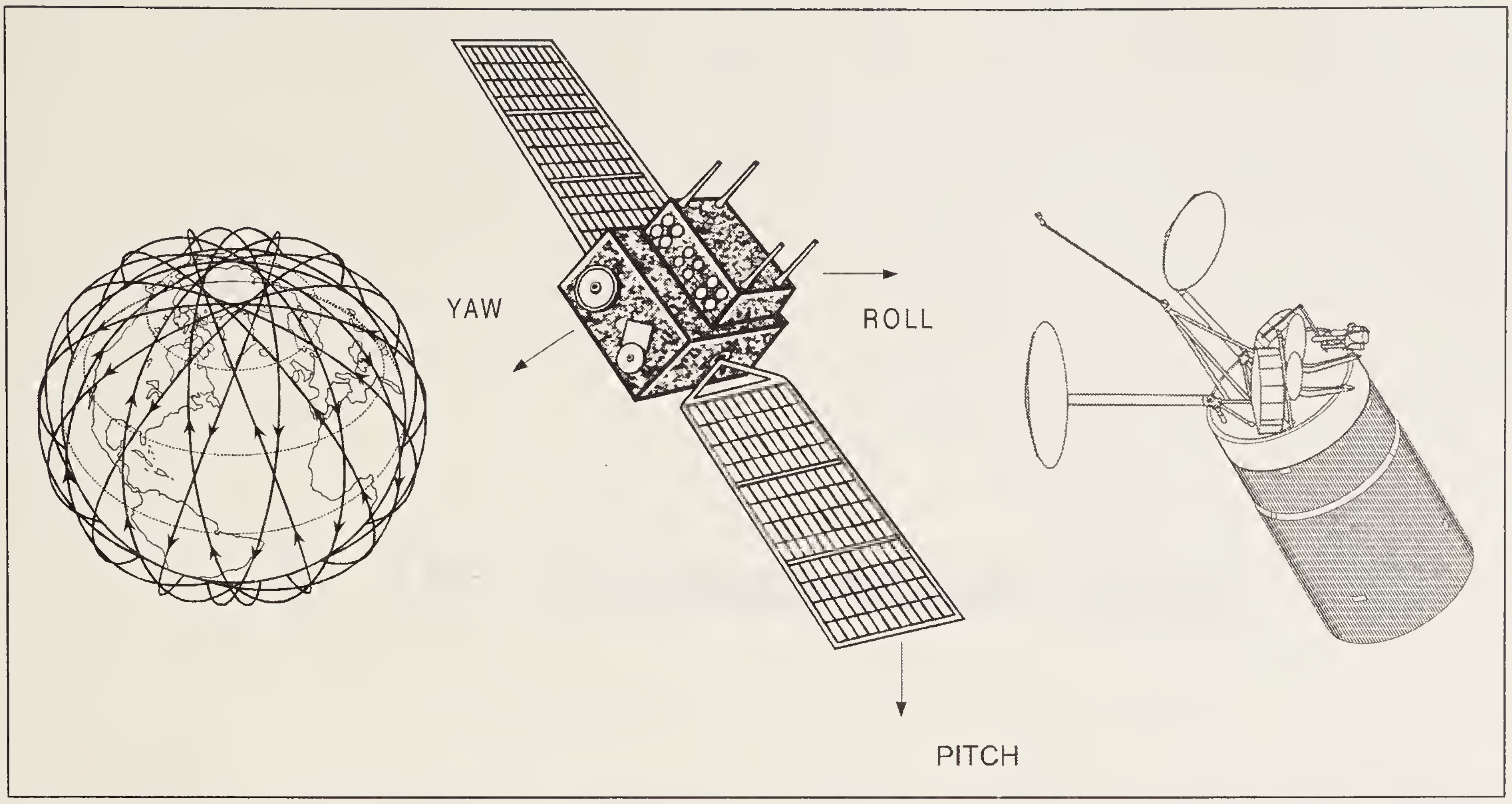


Fig 3.6 : Three-axis Stability maintained by satellites in orbit. The satellite maintains a fixed attitude relative to the orbital track and the Earth's surface. All movements of a satellite can be described as rotations about one or more of its three axes. viz., the roll axis in the direction of the satellite's motion; the pitch axis in the up and down direction and the yaw axis, which is perpendicular to the pitch axis (in the direction of the Earth), Reaction wheels, momentum wheels and gyroscopes as well as onboard thrusters are used to maintain the stability of a satellite in orbit. Some satellites are made to spin like a top keeping the antennas on a platform which is despun by counter rotation in relation to its body.

it in the up and down direction perpendicular to the roll axis, and the yaw axis which is perpendicular to the other two axes and enables the satellite's sensors to look at the Earth (Fig 3.6).

8. The Sunsynchronous Orbit

A frame of reference is required for fixing a satellite's orbit. Such a frame is fixed along three axes set at 90° to one another: one, along the equator from the Earth's centre (Y), another along the line linking the Earth's centre with the North Pole (Z); and the other, along the line from the Earth centre towards the First point of Aries in the sky (X).

An elliptical orbit around the Earth is defined by six elements (Fig 3.7).

1. Inclination or the angle (*i*) made, where the satellite's orbital plane intersects the equatorial plane (in IRS-1C, it is 98.12°);
2. Right ascension of the ascending node (marked by the symbol, Omega Ω), the angle made by the line of nodes at the point where a satellite crosses the equator from the southern to the northern hemisphere;
3. Semimajor axis (a) that connects the Earth centre with the perigee (for IRS-1C, the semimajor axis is 7195.1 km comprising 6378 km of the mean Earth radius and 817 km of the satellite's altitude);
4. Eccentricity (elliptical shape) of the orbit (e), (in the IRS-1C orbit, e is .0004);
5. Argument of perigee (marked by the symbol, small Omega (ω) that shows the angular distance to the perigee from the ascending node (the angle shows how far the perigee is from the equatorial plane (about 90° in the IRS-1C orbit); and
6. True anomaly: the angle made by the line from the Earth centre to the satellite and the line connecting the Earth centre with the perigee of its orbit (it shows the exact location of the satellite at a particular point of time).

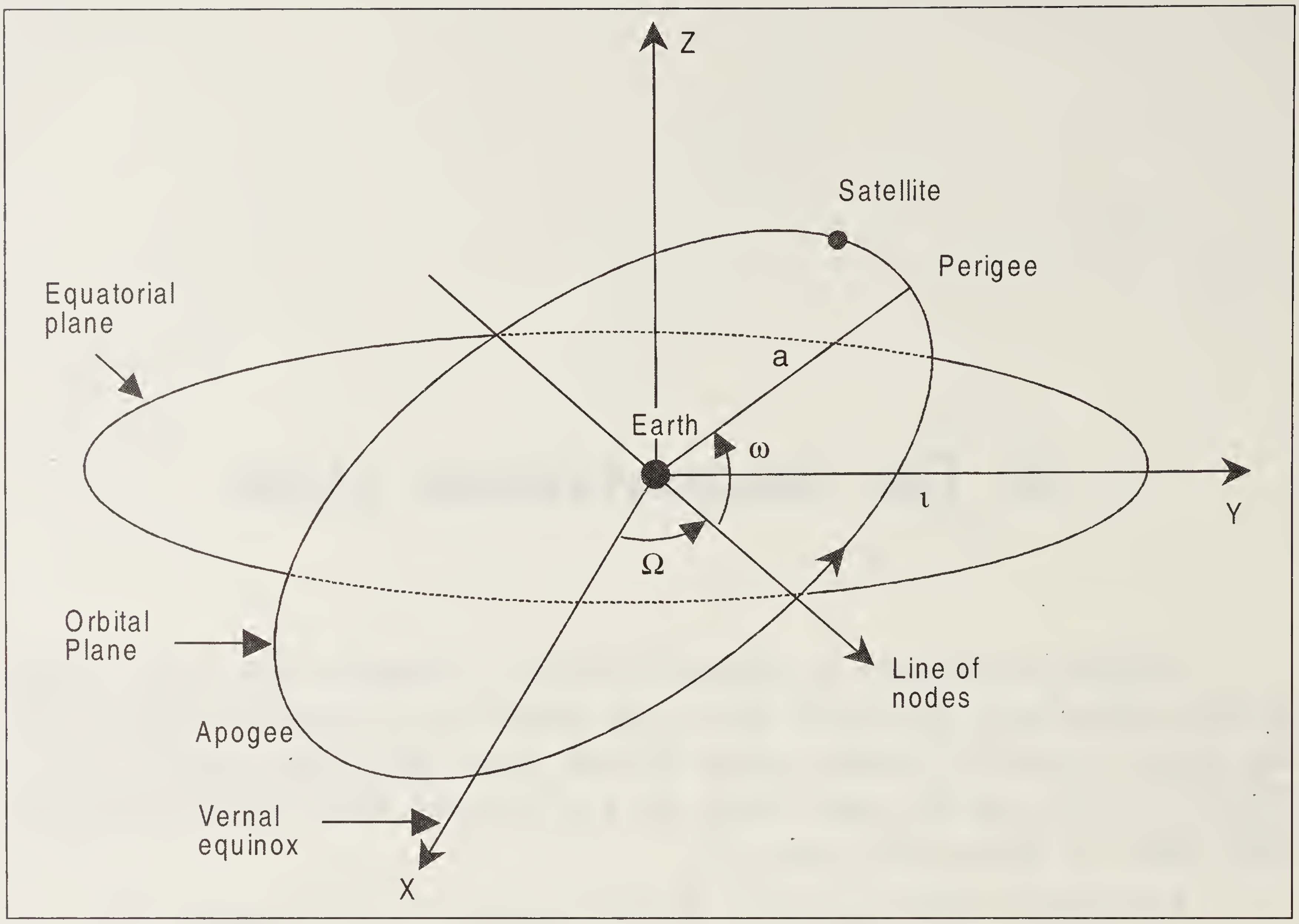


Fig 3.7 : Six Elements that define an elliptical orbit around the Earth.

The Earth's Shape and its Benefit

The Earth's shape affects the orbit of a satellite near it. One of the most useful low Earth orbits is called sunsynchronous. It is a circular orbit around 600 to 800 km from the Earth's surface (Fig 3.8).

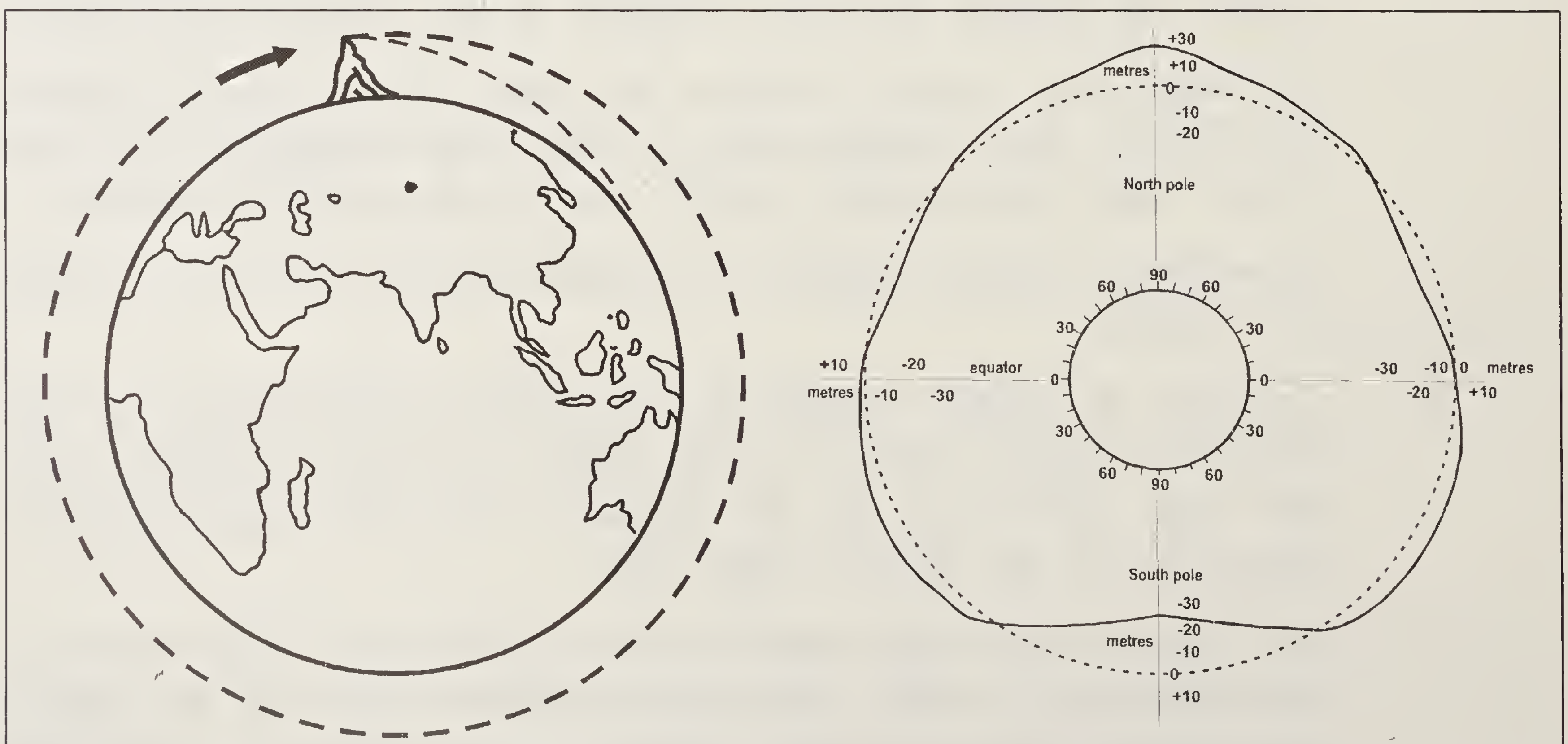


Fig 3.8 : The Earth is pear-shaped, with a bulge at the equator. A satellite has to gain a speed of about 8km a second to go into Earth orbit; otherwise the Earth's gravity will pull it down, even if it is hurled from a mountain.

The Earth's radius at the equator is 6,378.14 km as against 6356.79 km at the poles.

The pear-shaped Earth produces gravitational anomalies that affect the orbits of satellites. As a satellite crosses the equatorial region, the plane of its orbit will

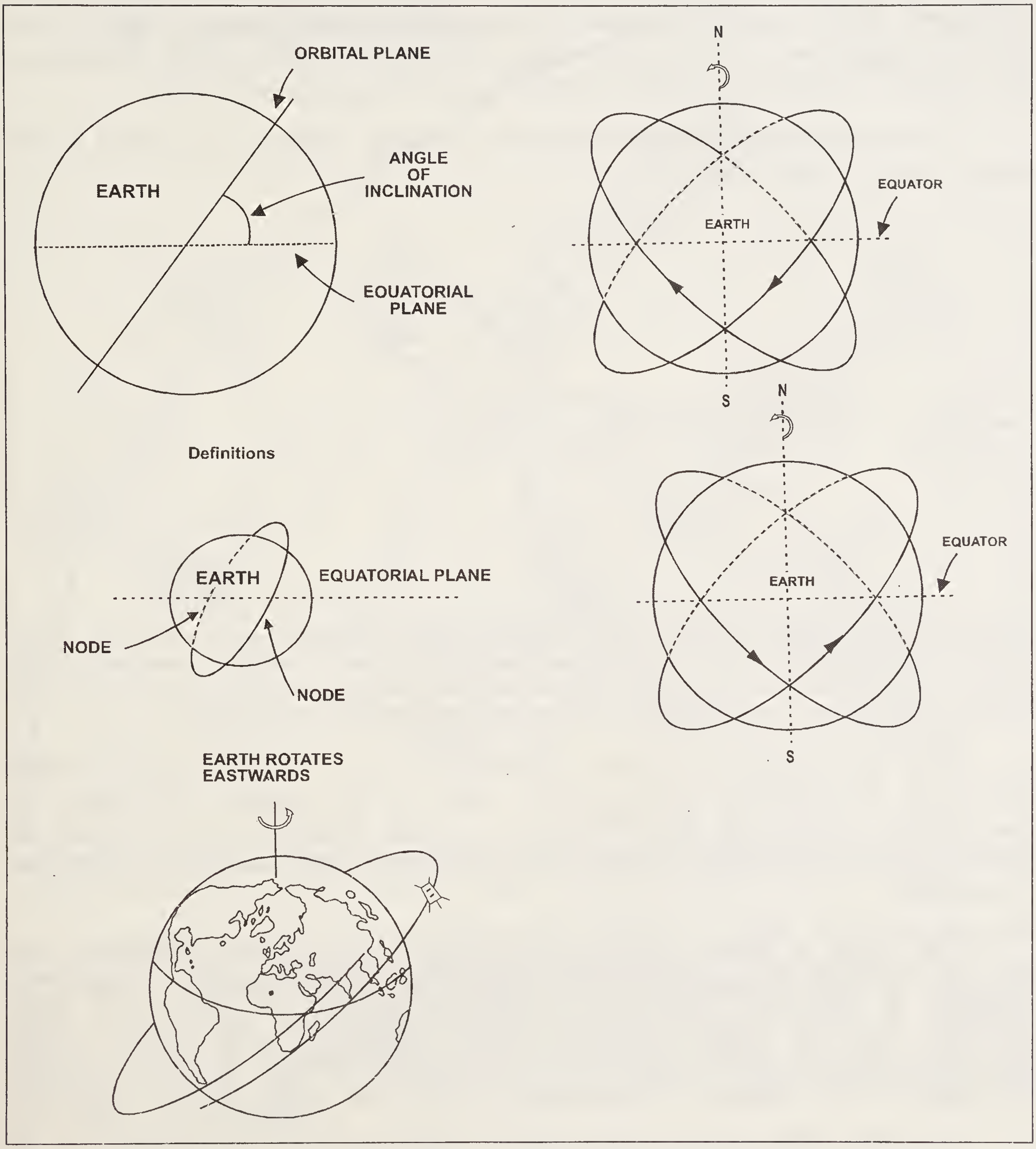


Fig 3.9 : Nodes are the points of intersection between a satellite's orbit and the equatorial plane of the Earth. Because of the equational bulge of the Earth, a satellite passing from the southern to the northern hemisphere in a west to east direction, will have westward regression and the orbit is called direct. If the satellite passes from east to west (also from the southern to the northern hemisphere), it will have an eastward regression, and the orbit is called retrograde.

shift because of the Earth's equatorial bulge. This is known as regression of the nodes. Nodes are the points of intersection between the orbit of a satellite and the equatorial plane of the Earth. When a satellite passes from the southern to the northern hemisphere in a west to east direction, the satellite will have a westward regression. If, on the contrary, the satellite passes from the east to west (retrograde orbit) from the southern to the northern hemisphere, it will have an eastward regression. The rate at which the regression takes place depends on the altitude of the orbit and its inclination to the equator (Fig 3.9).

The solar illumination angle desired for remote sensing can be fixed for the whole year in such orbits.

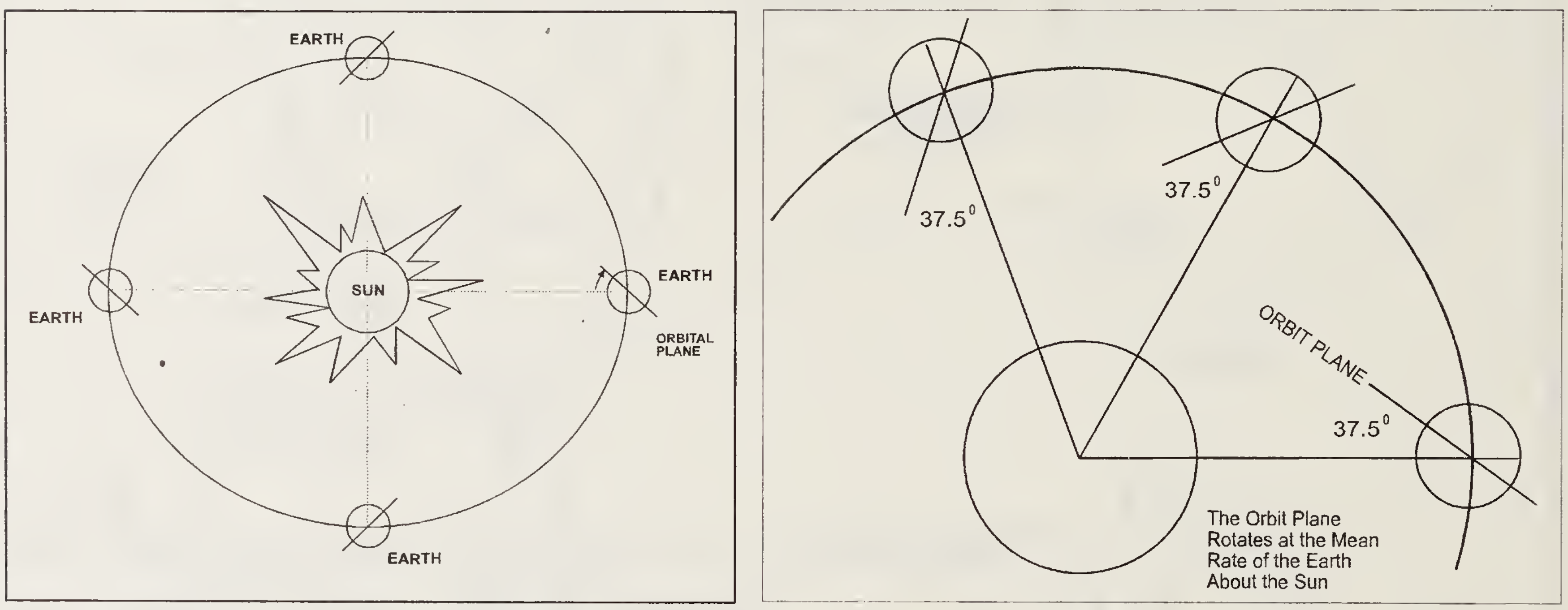


Fig 3.10 : The Earth's equatorial bulge makes the orbital plane of a satellite in an inclined orbit precess (rotate) by about one degree a day eastward to keep pace with the Earth's revolution around the Sun. This results in a sunsychronous orbit, where the angle between the Sun and the satellite's polar orbit plane stays constant throughout the year. Hence images of the ground can be had from the same angle.

One vital condition is that the satellite should go in an east-to-west direction. The angle of inclination of the orbital plane to the equator will depend on the altitude of the orbit (Fig 3.10). For example, Cartosat-1 at an altitude of 618 km has an inclination of 98.87°. Resourcesat-1 at 821 km has an inclination of 98.76°.

The orbits of Indian remote sensing satellites are polar sunsynchronous. For example, the orbital period of IRS-1A and of the identical IRS-1B is about 103 minutes. A polar, sunsynchronous satellite completes 14 orbits a day. Each successive orbit is shifted westward over the Earth because of Earth's rotation by about 25° of longitude, corresponding to 2,872 km at the equator (Fig 3.11).

The first orbit of the second day is shifted by 1.17° of longitude to the west corresponding to about 130 km at the equator. The satellite completes one cycle of coverage of the Indian subcontinent in about 22 days (i.e. 307 orbits). A satellite (e.g. Cartosat-1) revisits the same area every five days and with some adjustments in the orbit, the revisit time can be reduced to one day. The orbit

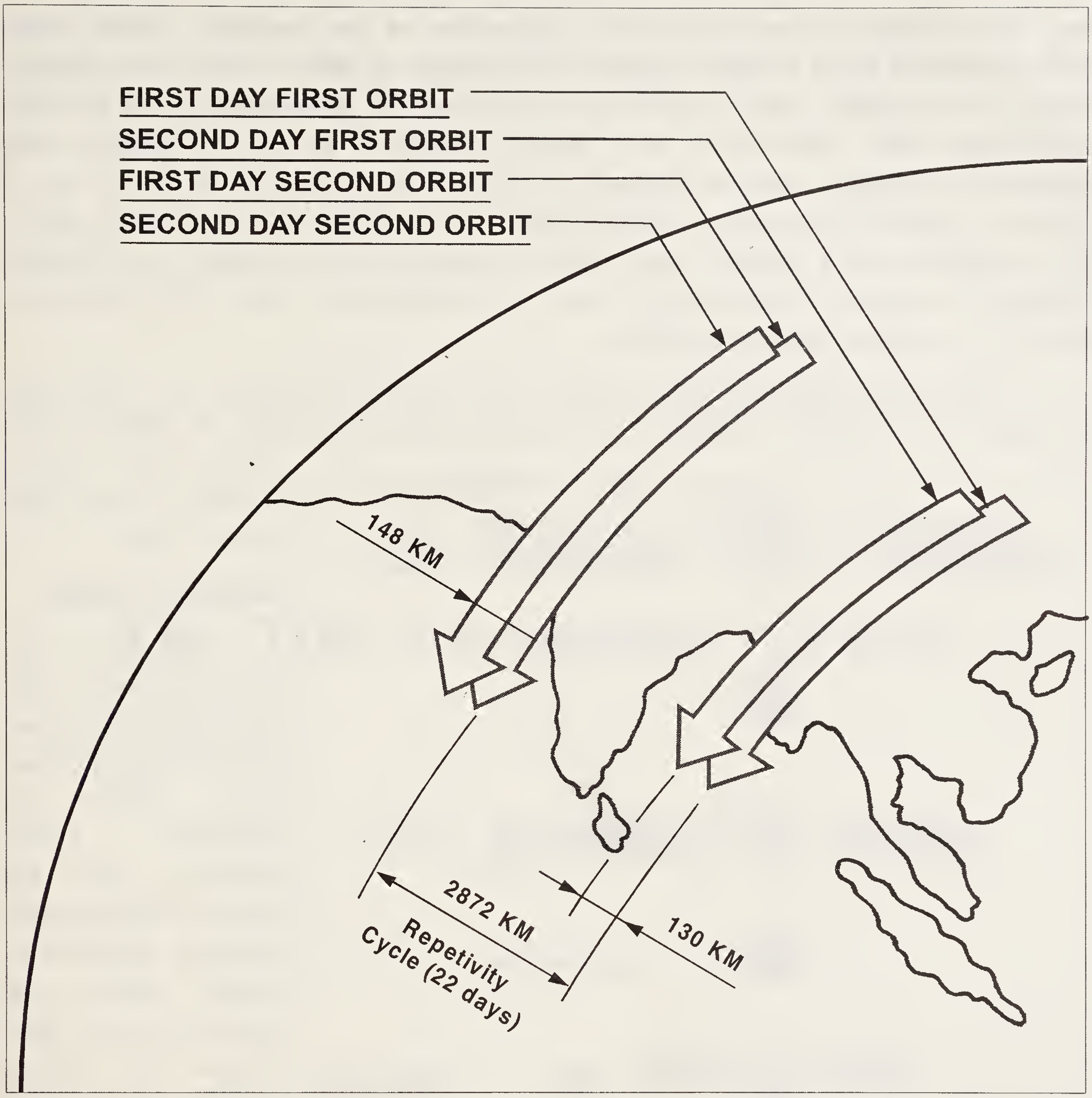


Fig 3.11 : A sunsynchronous satellite in polar orbit, completes 14 orbits a day. Each successive orbit is shifted westward over the Earth's surface by 25°.79 of longitude corresponding of 2872 km at the equator.

is so controlled that the ground track at the equator is within 14.8 km from the nominal path. The equatorial crossing time of the satellite (also known as the local time) is indicated by the angle between the descending node (of the satellite's orbit) and the Sun's projection on the equatorial plane. The time fixed for Cartosat-2 is 9.30 a.m.; it is 10.30 a.m. for Cartosat-1 and Resourcesat-1; and 12 noon for Oceansat-2.

Freezing the Perigee

The perigee and the apogee of the sunsynchronous orbit keep changing under the influence of various perturbations such as solar pressure and the Earth

drag. This change occurs even as the inclination of the satellite's orbital plane to the equatorial plane remains constant. The perigee of IRS-1C orbit, for example, which was nominally given as 817 km, could vary (if uncorrected) from 809 km to 825 km. This would result in a steady turning of its line of apsides (that connects the perigee and the apogee) at 3.6° a day. (Imagine a person on a swing in a giant wheel going up and down, but in different angles every day!). For a satellite, such a change would imply a variation in its altitude over different latitudes. The result is unacceptable, since it will change the scale of the imageries given by a remote sensing satellite.

Hence the apsidal motion is arrested by freezing the perigee, i.e. controlling its height at a specified distance by using thrusters periodically. In IRS-1C, the perigee was frozen at 809 km near the North Pole.

Different Orbits

Besides the geosynchronous and polar orbits, there are highly elliptical orbits, (also known as Medium Earth Orbits), used by some communication satellites. Satellites in higher orbits can provide more spot beams to serve specific regions (Fig 3.12).

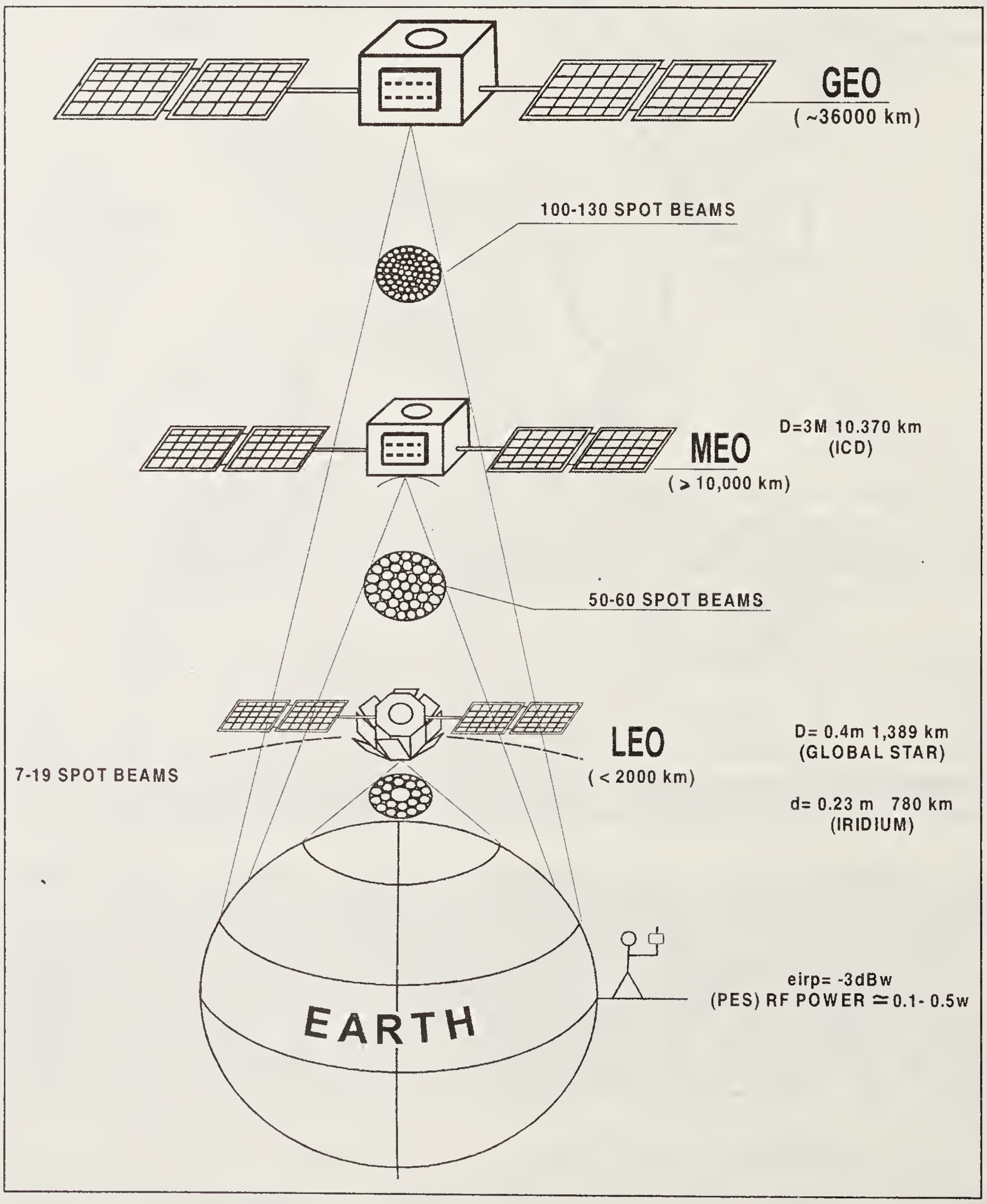


Fig 3.12 : Various Orbits. The geosynchronous or geostationary orbit is a circular orbit above the Earth's equator at about 36,000 km. Low Earth Orbits (LEO) include polar sunsynchronous orbits (at about 600-800 km) in the north-south direction and highly elliptical orbits (about 10,000 to 20,000 km).

PART - IV

ON THE LEARNING CURVE

9. A Flop is a Flop

Based on the experience of designing and making sounding rockets, ISRO started to build a satellite launch vehicle. Scale models were fabricated and tested at the Indian Institute of Science and the National Aeronautical Laboratory in Bangalore. The engineers knew the theory but wanted to confirm the exact requirements of a flight model. For example, they wanted to ascertain how the rocket would behave during its take-off through the atmosphere and during its transit through thin air and vacuum, the effect of stage separation, pressure distribution and the influence of the lower stage on the upper one, etc. In order to find out the technical data on these and related features, scale models of rockets were taken to Porz Wahn near Cologne in Germany for tests in wind tunnels. Engineers from Thumba watched the models float steadily inside the tunnel, while TV cameras mirrored the behaviour of the models on the control panel. The wind tunnel could simulate various levels of atmospheric pressure and wind speeds. Hypersonic speed tests up to Mach-8 (eight times the speed of sound) could be conducted there.

That was in late 1973. By then designs of several subsystems had been finalised for realising a four-stage rocket, called SLV-3, powered by solid propellants. A four-year schedule was drawn up. SLV-3 became a major national venture, involving eventually some 46 organizations in the public and private sectors. It took six years to develop the first experimental flight model (Fig 4.1). When SLV-3 was designed, the diameter of the biggest Indian rocket was only 560 mm. Rohini-560 could take a payload of 100 kg to a height of 350 km, but it could not achieve an orbit. A satellite can go into Earth orbit only if it is hurled horizontally at the appropriate speed (e.g. at 7.61 km a second at an attitude of 500 km). The thrust for this has to depend on the propellants. The size and weight of the propellant segments and the rocket motors made in Thumba determined the basic configuration of SLV-3. For its first stage, for example, it was decided to link three rocket motor segments into one. The rocket's total length was 22.7 metres, and the diameter of its base was one metre.

Of its total weight of 17 tonnes, propellants accounted for 13 tonnes. The fourth stage, which gives almost one half of the required speed of 28,000 km an hour to the satellite, weighed only two per cent of the total vehicle system.

The stages were interconnected by aluminium alloy parts. The interstages had separate controls and separation systems.

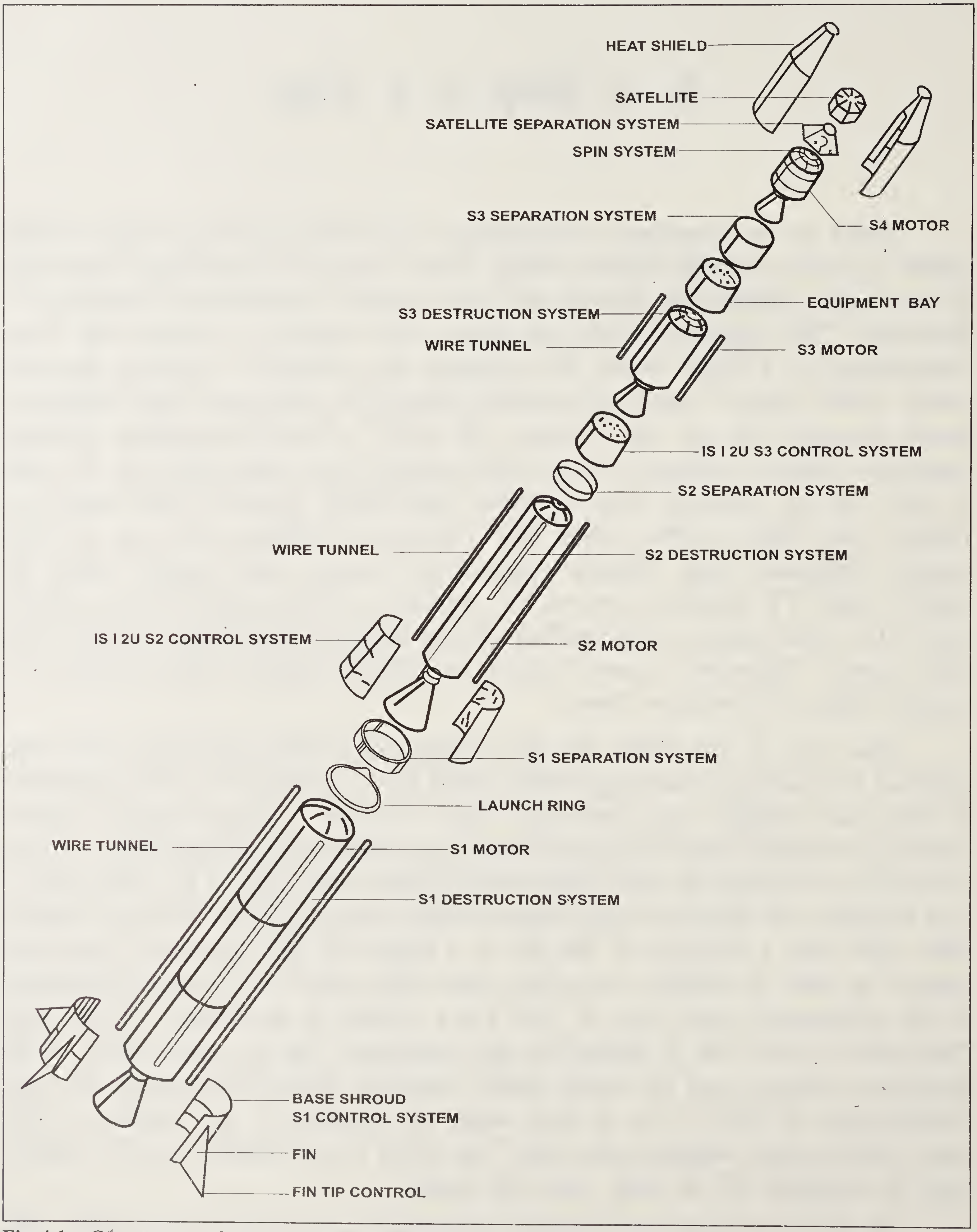


Fig 4.1 : Cómponents of the first satellite launch vehicle SLV-3

Different types of controls were adopted for the various stages. The first stage had what are known as secondary injection thrust vector control (SITVC) and fin-tip control.

When a rocket begins to give thrust on ignition, it has to overcome enormous aerodynamic forces in the atmosphere. In order to move the vehicle along the predetermined course, the thrust itself is controlled by injecting a fuel, strontium perchlorate, to create a side force called thrust vector control (TVC). This system was included in the first stage of SLV-3. After the initial moments, thrust vector control becomes a back-up system, intervening only when another system, called fin-tip control, becomes inadequate to cope with the forces acting on the rocket. Fins at the bottom of the first stage can be tilted by plus or minus 15°. With the movement of fins, aerodynamics stability of the vehicle improves. The behaviour of the fins was studied in simulated conditions on the ground.

The first SLV-3 : A Flop

The first SLV-3 was launched on August 10, 1979, a year after the targeted date from Sriharikota (SHAR). Prolonged applause by scientists in Mission Control greeted the lift-off. The multi-stage rocket climbed high leaving a glowing orange trail. But the elation was short-lived. Telemetry data revealed that the last stage of the rocket had plummeted into the Bay of Bengal, five minutes and 15 seconds after the take-off. The 40 kg technological payload it carried also went down with it. The splash-down occurred about 500 km south-east of SHAR. Top space scientists immediately went into a conference to analyse the results. Four hours later, the mission was described as "partially unsuccessful". A stroke of beginner's luck, which the scientists expected, evaded them. The space programme suffered a setback, though the mission was only the first of three planned test flights. The experience was totally new to the country. One newspaper described that a flop is a flop, irrespective of the gains claimed.

The then Chairman of ISRO, Prof. Satish Dhawan himself admitted the failure and took the blame upon himself, though Dr Abdul Kalam was the Project Director. (Later, Prof. Dhawan gave full marks to Dr Kalam, when the second attempt succeeded). Recalling these events, Dr Kalam pointed out that "The magnanimity of Prof. Dhawan in dealing with the failure of the first launch and his motivating and leading us towards success in the very next flight is one of the basic foundations of a great ISRO culture."

Was it really a flop? An analysis showed some interesting details. It was found that the first stage had functioned normally. Its motor burnt as predicted. Its controls, both fin-tip as well as thrust vector, worked well. The rocket reached three km higher than the expected 20 km. However, 68 seconds after the lift-off, the second stage ran into trouble. A jammed valve in the second stage

reaction control system resulted in a leak of the oxidizer on the launch pad itself. As a result, the stage was not stabilised. The vehicle tumbled. Later, the third stage recovered a little, but could not gain the full velocity needed. By itself the stage performed well. Then the third stage separated as planned, but could reach only 65 km instead of 127 km. It was followed by the programmed long coasting (when the motors do not thrust) of the fourth stage for 232 seconds, along a ballistic trajectory. As the initial altitude reached was lower when the rocket began its curved path, it fell into the sea. The thrust levels of different stages were normal and the real-time tracking of the rocket was done successfully. There was indeed some beginner's luck. About 70 per cent of the systems worked normally.

A Successful Attempt

When it was found that there was nothing wrong with the basic design of the rocket, the engineers resumed their work. The malfunction in the control system of the second stage was set right in the next attempt. The only change made was in the valve assembly.

On 18 July 1980, the range in Sriharikota was again readied for a launch. The sea was calm and free of ships and fishing boats. Nor was there any plane in sight. All had been alerted. Tracking stations at Sriharikota, Thiruvanthapuram, Ahmedabad and Car Nicobar went on the alert. The count-down proceeded. A minor fault was set right. The lift-off occurred at 8 hours, 3 minutes and 45 seconds, IST. A thunder rolled down the nearby casuarina forest. The rocket rose on a column of orange flame and soon disappeared into the clouds. The signals were loud and clear. The control consoles in the underground block-house near the launch pad showed that everything was normal. The stages separated as planned reaching the programmed altitudes. The second stage, which had trouble in the first mission, functioned normally, taking the rocket to 92 km, while almost doubling the speed. The performance was close to prediction as revealed by the subsequent analysis of the data received.

At a height of about 300 km, a satellite, Rohini-1 was injected into orbit at a speed of 7.79 km/sec or 28,000 kmh. Rohini was thus put into orbit within eight minutes from lift-off. The 35-kg satellite started transmitting signals clearly. Its solar panels, which converted sunlight into electricity, worked well. The on board instruments sensed the speed, direction and spin rates and transmitted the data. Careful use of onboard gas and system management extended the mission life of the satellite. It ended only on August 1, 1981, after about two years in orbit. By April that year, it had completed 10,000 orbits, including 638 tracked by Indian stations. During 184 orbits, the satellite's TV camera operated and the entire country was covered thrice. Even after the end of its useful life, its spin stability was maintained and the silent craft was tracked once a week.

An Unplanned Spin

Following the successful flight of the experimental model, ISRO decided to launch a development model (SLV-D1). The launch window was fixed between May 22 and June 5, 1981. On May 20, a check-out revealed some snags. The vehicle had to be taken back for repair. The count-down was resumed on May 28. Though there were minor snags, they were quickly cleared. The launch took place on May 31, 1981 at 9.03.46 IST, covered live by All India Radio and Television. After 80 minutes of suspense, the seven-storey tall SLV-D1 leapt into space with a roar of hundreds of freight trains, riding a column of bright yellow flame with a tinge of red. Its main objective was to evaluate the vehicle's performance for operational missions. SLV-D1 carried for the first time an Indian-built inertial measuring unit, and a landmark camera for qualifying solid state components useful for remote sensing operations. Another new feature of the mission was the use of an on-line computer for receiving telemetry data directly from the satellite. In earlier missions, data were received by a telemetry station and transported to the computer centre.

Mission Control heaved a sigh of relief. The first stage ignition was normal. The liftoff at T+0.4 sec was as planned. The onboard vehicle attitude programmer and sequencer were initiated correctly. The downward pitch of the vehicle started as scheduled at 5.8 seconds. The thrust vector control and fin-tip control functioned properly. The first stage burnout was normal at 52 sec at an altitude of 18.2 km, and the vehicle attained a velocity of 1050 m/sec. But at 62.8 second (sec) the vehicle's movement showed an unplanned, slow spin. However, it was not considered critical. The first stage separated as planned at 72.7 sec. The slow spin caused deviation from the planned pitch (up and down) and yaw (right and left) manoeuvres. Orientation errors built up, even as the vehicle was attaining or even exceeding the planned flight altitudes. Subsequent analysis (made after the flight) revealed that these errors could not have been fully corrected later.

The second stage, it was found, actually reduced the attitude error but could not fully correct it. The stage itself performed normally and burnt out at 74.6 km (1 km higher than predicted) at 121.3 sec. But it attained a velocity of 2320 m/sec which was six per cent lower than predicted. After the separation of the heat shield, the third stage burnt out at 188.3 sec at an altitude of 147.8 km, but the velocity reached was lower by 3 per cent. Actually, the stage performed slightly better than predicted. Some errors in pitch and yaw were controlled but the unplanned spinning continued, resulting in the lower velocity.

The separation of the third stage, the subsequent spinning of the fourth stage, its ignition and the separation of the satellite, Rohini, occurred as planned. The fourth stage provided a little more thrust than intended and completed the burn-out at 430 sec and injected Rohini into orbit. The injection altitude was 304

km, 6 km (or 2 per cent) lower and the injection velocity was 7763 m/sec, which was one percent lower than predicted. The direction of motion of the satellite was 0.5° lower and 1.8° more towards the south than planned. Ten minutes after launch, the orbit was predicted to be 263 km by 426 km, assuming no orientation errors. Some 96 minutes after launch, the orbit injection was confirmed during the satellite's first pass over VSSC. In subsequent orbits, it was tracked by ground stations in Sriharikota, Bangalore, Ahmedabad, Thiruvananthapuram and Fiji. More tracking data were available in the next four days and it was found that the actual orbit achieved was only 183 km by 426 km. The apogee and perigee of an orbit are very sensitive to the velocity and angle of injection. The orbital parameters indicated that the life of the 38-kg satellite would be less than a month as against three months predicted earlier. (Actually, the satellite came down after nine days in orbit). When this was known, an attempt was made to test the landmark sensor in the time available. For a proper working of the sensor, the spin rate of the satellite had to be brought down to about 10 revolutions per minute (rpm). As that would take some time, it was decided to operate the sensor when the spin rate of the satellite came down to 58 rpm from about 100 rpm. The payload operation was normal, though useful pictures could be taken only when the despin operations were complete.

The lower orbit could not sustain the satellite for long. In its 131st orbit, the satellite was tracked over Fiji on 8 June, when the onboard temperature revealed a steep increase. Subsequently, the satellite disappeared and could not be tracked. It was later computed that re-entry probably occurred over the Atlantic on June 9 at about 10.00 a.m. at 25° North latitude and 40° West longitude. Subsequent analysis of the data revealed that one of the four fins of the first stage motor did not respond to the commands sent to it from the onboard autopilot after 61 seconds. There were also initial problems of communication with the satellite. Though this was overcome, the mission was short-lived. It is however noteworthy that the Mission accomplished the primary task of orbiting a satellite, despite the severe lateral acceleration experienced.

It was pointed out that the thrust as well as the burn time of all the four stages were close to or better than the predicted values. The fourth stage performed normally, exceeding the predicted thrust.

Text-Book Precision

The second development flight of SLV-3 was a complete success. After 18 months of preparation, the launcher with an improved fourth stage, blasted off from Sriharikota on April 17, 1983. The launcher functioned with text-book precision. Within 10 minutes, it put a 41.5 kg Rohini satellite into near-Earth orbit. The

computers updated the trajectory every tenth of a second. The planned orbit (of nearly 400 km by 850 km) was achieved.

The fourth stage weighed 10 kg lighter than the earlier ones, mainly because of the Kevlar reinforced fibre used. As a result, more fuel (50 kg) could be taken. The fourth stage, though forming only two per cent of the total weight contributed 50 per cent of the orbital velocity. Inclined at 45° to the equator, Rohini circled the Earth every 99 minutes. It carried a solid state camera, called SMART sensor, which took images for identifying landmarks. It was described as an 'intelligent' camera as it did not take pictures when there were clouds above the target area. The satellite ended its mission on September 24, 1984.

The main objective of launching SLV-3 with an improved fourth stage was achieved. Being the last in the development series, the successful mission boosted the confidence of the engineers and scientists and encouraged them to undertake the launching of a 150-kg satellite into near Earth orbit.

10. Learning From Failures

A year after the targeted date, the first SLV-3 was launched in 1979. It was partly successful. A jammed valve in the second stage reaction control system resulted in the leak of oxidizer on the launch pad itself. However, the data on the stages were encouraging.

In the subsequent light in 1980, the only alteration made related to the change of the valve assembly. The second SLV-3 was an unqualified success. Two more successful missions were accomplished in 1981 and 1983, respectively. In 1982, it was decided to develop an augmented SLV (ASLV) primarily as an intermediate vehicle for validating many complex technologies for use in operational launchers. Initially, two developmental flights were envisaged in 1987; two more flights were approved. Even at this stage, the blue-print for a polar SLV was drawn up. ASLV's payload capacity was increased to about 150 kg by adding two strapons to the fist stage, each of which was equivalent to the first stage of SLV-3. The strapons constituted the zeroth stage.

The ASLV mission involved more than just adding two strapons; it needed complex technologies: new types of nozzles, bulbous metallic heat shield, closed-loop guidance system and inertial navigation system, a new launch pad and a mobile service tower. ASLV was a solid propellant vehicle weighing about 40 tonnes.

The first developmental flight (ASLV-D1) on 24 March 1987, five years after the project was approved, failed. The first stage motor did not ignite, after the strapons separated. The cause was traced to an inadvertent short circuit in both the ignition systems. The mechanical safe arm device malfunctioned. Several modifications were made for the next mission, ASLV-D2, launched on 13 July 1988. The mechanical safe arm device was replaced by an electrical one; the pyro initiators were given extra capacity. The two strapons ignited simultaneously, following which the first stage was ignited as programmed. But at 49.1 seconds after the lift-off, the yaw and roll rate of the vehicle became abnormal. The yaw error was 1° as against 0.2° in the ASLV-D1 flight, at the end of the strapon burnout. This resulted in the severance of the vehicle at the top at 50.4 seconds after the lift-off. The strapons could not be separated though the equipment bay

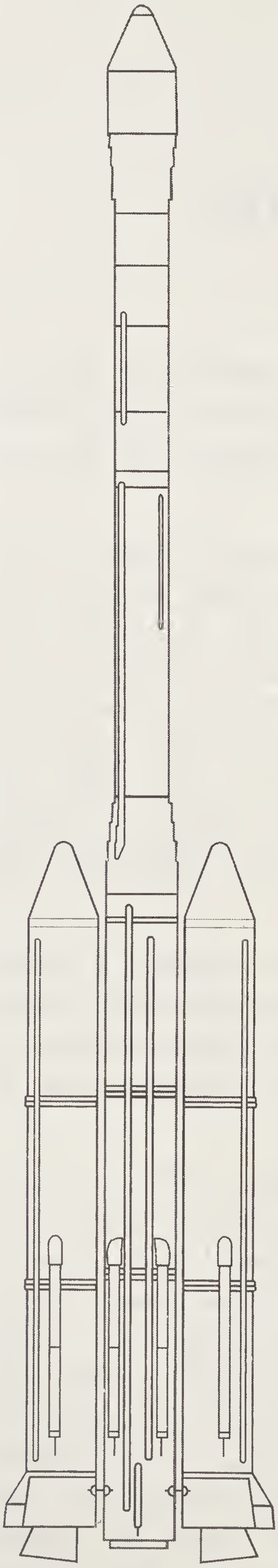


Fig 4.2 : ASLV-D4

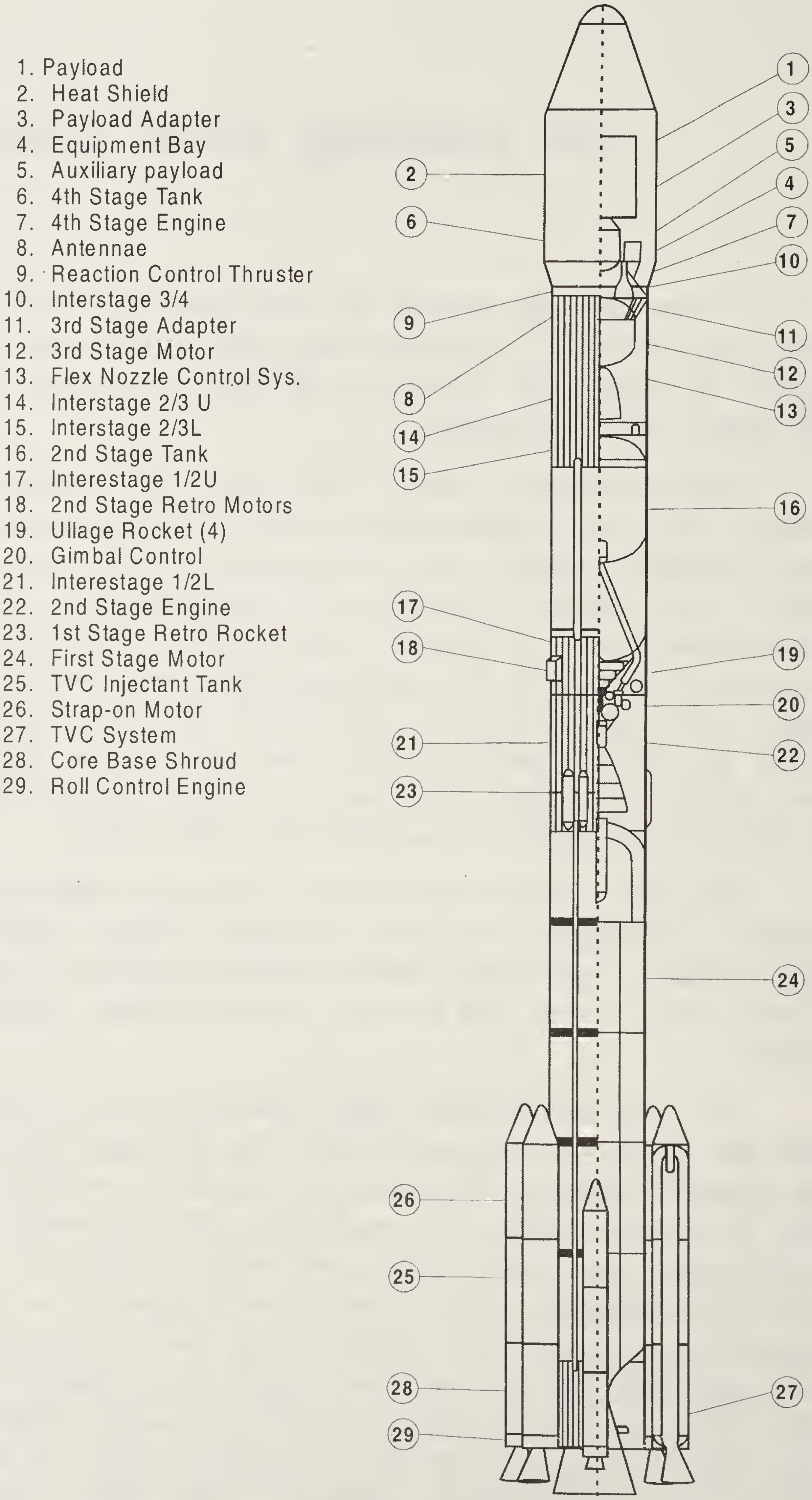


Fig 4.3 : PSLV Configuration

on the rocket issued the necessary commands. Still the first stage motor with the burnt-out strapons went farther. The performance of the stage till its burn-out at 97.8 seconds after launch as well as the SROSS satellite (which got prematurely detached) were found to be quite normal.

An investigation revealed that during the transition from the strapon burnout to the core stage thrusting, the control was inadequate (for 3 to 4 seconds) to correct the yaw error. The flight loads exceeded the limits. The full impact of an earlier burnout (by less than two seconds) of the strapons was not realised in static tests. The control from the core motor could not correct the error. The autopilot could not cope with it. Unusually high winds and gusts compounded the problems, beyond the capability of the control system.

Given its length-to-diameter ratio, ASLV is a highly unstable vehicle. And most important events (e.g. ignition of the core stage, strapon separation) occur at the edge of the troposphere where the dynamic pressure is high and winds could be severely forceful. However, the failure analysis revealed no major technological problems which were beyond the competence of ISRO.

Several changes were made for the next flight. Two passive fins were added to improve the aerodynamic stability of the vehicle. The autopilot was strengthened. Onboard real time decision-making was introduced to determine the sequence of flight events based on the actual performance (such as the first and second stage ignition and second stage separation). The design of the strapons was modified to reduce the maximum dynamic pressure, and a spin bearing between the third and fourth stages was eliminated to simplify the system. The fourth stage was improved by using Kevlar fibre and by increasing the length of the motor to hold more propellant. The nozzle was redesigned. As the strapons had to perform almost at the same time without any mismatch, the propellants were simultaneously cast for three segments so that one could be ground - tested. In addition, a faster burning propellant composition was used in one segment. In fact, an indigenous propellant (HTPB) was used in the core first stage and the strapons, instead of a propellant that was withdrawn under an international embargo.

The vehicle structure was strengthened. Wind data for over 10 years at the launch site were studied. Controls were checked. The vehicle's bending modes were reviewed. Computer studies were made in hundreds of tests to evaluate the vehicle's behaviour. The gap between the vehicle and the umbilical tower was increased to allow for the impact of fins and worst winds. Additional (300 kg) fuel was provided for the roll control system.

The modified ASLV-D4 was launched on May 20, 1992. The countdown was flawless. Subsequent events were satisfactory. However, the fourth stage achieved a spin rate of 80 revolutions per minute (rpm) as against the programmed

140 rpm. As a result, the satellite (SROSS-C, an engineering model) was injected into a lower orbit of 433 x 267 km as against the planned circular orbit of 475 km.

A Text-book Launch

The spin-up system of the fourth stage with the satellite in ASLV D4 was redesigned using spin rockets. The guidance system was refined to use additional energy of the lower stages to achieve a higher perigee. ASLV-4 took advantage of the lessons learnt from PSLV-D1 also. Accordingly, the onboard software was evaluated to avoid any malfunctions. The satellite's (SROSS-C2) weight was increased from 106 kg to 113.4 kg and the perigee height was changed from 450 km in ASLV-D4 to 400 km. It was actually placed in an orbit of 437 x 938 km. Orbit correction capability was introduced in the heavier satellite. Also for the first time, indigenously developed nickel-cadmium batteries were used. But the main features of ASLV-D3 and D4 were almost identical (Fig 4.2).

The reliability of pyro systems and electrical circuits was increased. The telemetry measurements were reduced from 253 to 189. The weight of the electronic packages was also reduced.

The mission of ASLV-D4 on May 4, 1994 was described as a text-book launch. After a flawless countdown, the rocket rose vertically for 5 seconds.

The vehicle soon came under the control of the open loop guidance till the separation of the first stage and ignition of the second. Later, the closed loop guidance took over until the third stage separated. The closed loop guidance system compared the attitude, velocity and orientation of the vehicle at every second with the targets given and computed the orientation needed and the velocity to be gained to reach the target. The errors were computed by the digital autopilot and given to the control system. After the satellite was injected into orbit and the fourth stage was separated, the spin was reduced by the satellite itself. Real time decision making was introduced to sequence the events such as stage ignition and separation. The aim was to avoid the so-called no-control zones during the transition to the first stage from the strapons and from the first to the second stage. In the former case, there may be no control for a while and in the latter, there may be collision of the separated stage with the rest of the rocket. All the events occurred as predicted. The strapons provided identical performance. Only at the third stage burnout, a higher velocity of about 50 metres a second was recorded. The "over performance" was anticipated. For the first time, the vehicle was tracked upto a range of 1800 km. Data on the motor pressure of the fourth stage were available at the launch base in real time. It was confirmed that the stage had performed as predicted. The vehicle was under control all the time and the system worked so well that the control motor propellant was not fully consumed.

It is noteworthy that the first two ASLVs did not receive the ignition signal because of other malfunctions in the system. Though the first two ASLV missions failed, the detailed post-flight analysis enabled ISRO to refine the design and carry out improvements. The ASLV missions yielded several technological gains: strap on technology, inertial navigation, closed-loop guidance, microprocessor-based onboard computer, real time decision-making on board, metallic heat shield in bulbous shape, vertical integration of the vehicle, and design for better control.

With the successful launch of ASLV-D4 on 4 May, 1994, all the objectives envisaged under the ASLV programme were fully realised.

Indian rocket technology is largely self-reliant. The steel for the rocket motor casing is fabricated by Indian industries. The HTPB binder, phenolic resin and high-silica cloth are all based on the ISRO technology. Ammonium perchlorate is also produced in the country.

PART - V

PSLV: ISRO's WORKHORSE ROCKET

11. Four Stages and an Anomaly

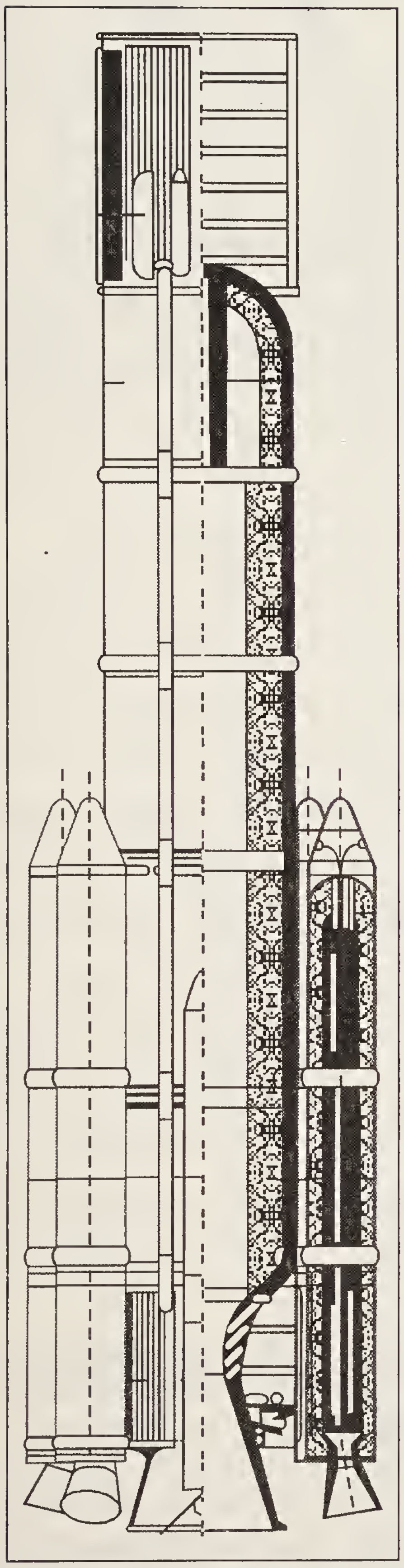


Fig 5.1 : PSLV-First Stage: The core motor case is made of maraging steel. Six strapon motors provide additional thrust.

The polar satellite launch vehicle (PSLV) is designed to place an Indian remote sensing satellite weighing one tonne in a 900 km polar sunsynchronous orbit. After some initial teething problems, the rocket became ISRO's workhorse.

The PSLV has four stages (Fig 4.3). Solid propulsion system is used in its first and third stages and liquid propulsion motors in the second and fourth stages. The 44-metre tall vehicle's take-off weight is about 283 tonnes. A total of 2,500 elaborate drawings were necessary to make the rocket.

The first stage, rated as the third largest solid booster in the world, is equivalent to 14 times the core of an ASLV. The stage has a 2.8 m diameter core motor made of maraging steel, as against 1 m in ASLV. The stage uses solid propellants based on HTPB and ammonium perchlorate developed in VSSC and produced by the Indian industry. The propellant is cast in five segments weighing in all 129 tonnes. The stage gives a maximum thrust of 4,500 kN. Six strapon motors provide a maximum thrust of 662 kN each. Only two strapons are fired on ground at lift-off and the others in the air with a view to ensuring proper load on the vehicle. The first stage quickly takes the vehicle through the dense atmosphere (Fig 5.1).

The second stage (2.8 m dia) carries 37.5t of liquid propellants UDMH as fuel and nitrogen tetroxide (N_2O_4) as oxidizer (Fig. 5.2).

The engine is fed by a turbo-pump which in turn is run by a gas generator. The propellants are taken into a thrust chamber where, being hypergolic, they undergo spontaneous combustion. The resulting hot gases are expelled through a convergent-divergent nozzle. The stage provides a

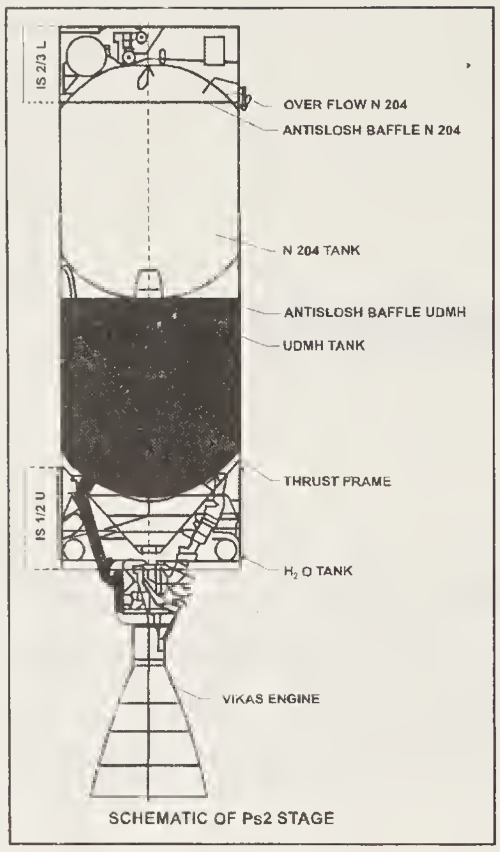


Fig 5.2 : The second stage uses liquid propellants. The engine is fed by a turbo pump, which is run by a gas generator.

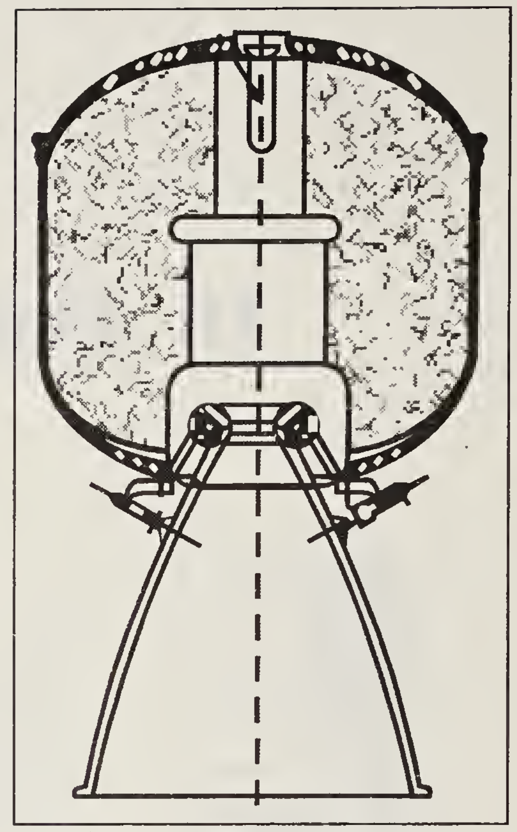


Fig 5.3 : The third stage uses solid propellants. It lifts the vehicle to about 400 km.

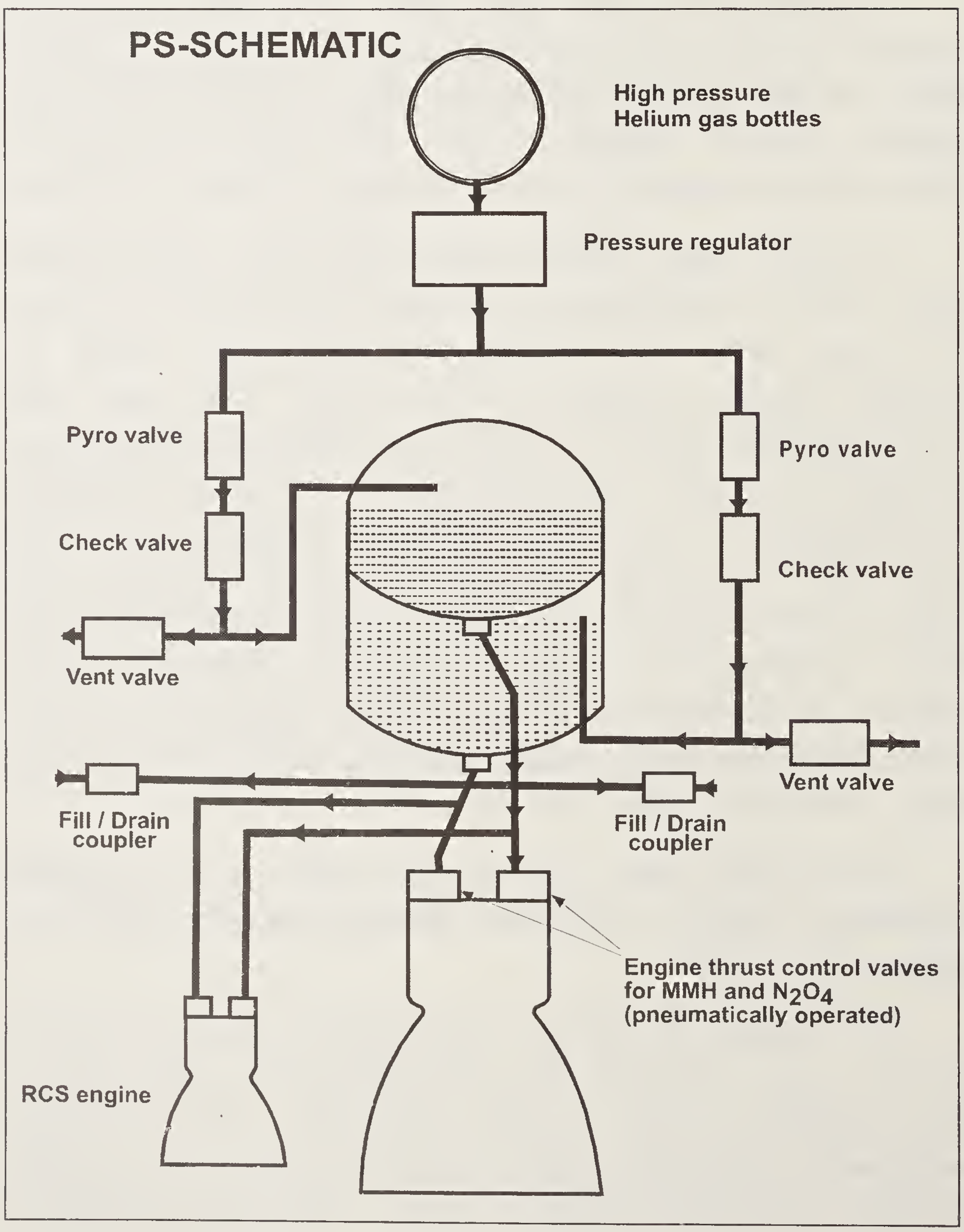


Fig 5.4 : PSLV Fourth Stage: The stage uses mixed oxides of nitrogen as oxidiser and monomethyl hydrazine as propellant. The fourth stage liquid engines are presure-fed, unlike the pump-fed engine in the second stage. Helium gas stored under high pressure is used to push the propellants into the combustion chamber.

maximum thrust of 725 kN in vacuum. The technology is based on the Viking engine used in the European Ariane rocket. The solid third stage (2 m dia) carries 7.2 t of HTPB and gives a maximum thrust of 340 kN (Fig 5.3).

The fourth stage has two liquid engines. It uses two tonnes of N_2O_4 as oxidizer and monomethyl hydrazine as propellant (Fig 5.4).

The liquids are stored in a titanium alloy tank. (The alloy reduces the mass of the stage). The fuel itself is used to cool the combustion chamber and part of the nozzle, before it goes to the injector. Each of the two engines provides thrust of 7.4kN. The fourth stage has a propellant acquisition system which facilitates its ignition during the coasting period (when the engine is off) between the burnout of the third stage and the ignition of the fourth stage. (There is another coasting period between the fourth stage burnout and separation of the satellite). During coasting, the vehicle is in a weightless condition and the liquid propellant may get mixed up with the pressurant helium gas, but the propellant acquisition system ensures minimum gas-free propellant for the engine to operate. Each stage has its own control system. In addition, several auxiliary systems separate the stages and the heatshield.

Nominally, the first stage lifts the vehicle to an altitude of 56 km reaching a velocity of 2 km per second before burning out. The second stage takes the vehicle to 250 km at 4 km/s velocity. The third stage lifts the vehicle to 400 km and increases the velocity to 6.3 km/s. After a long coasting period of 273 seconds, the fourth stage starts burning at 80 km and inserts the vehicle in the desired orbital altitude of 904 km and provides a velocity increment of nearly 2 km/s. The stage will be shut off once the orbital velocity of 7.4 km/s. The fourth stage liquid engine is pressure-fed, unlike the pump-fed engine in the second stage.

The propellants are pushed into the combustion chamber of the engine by helium gas stored under high pressure (of over 300 atmospheres) in gas bottles made of titanium alloy. The propellants flow up to the thrust control valves of the combustion chamber. Helium is also used to purge the engines, when they are shut off to prevent burning or migration of propellants. Helium, though notorious for leaking, is light and inert and is good for applying pressure.

An Unexpected Malfunction

The first development flight took place on September 20, 1993 from SHAR. The rocket launched a 846 kg satellite. The rocket did not attain sufficient altitude and velocity because of an error in the control software implementation; however, practically all of the subsystems were proved in flight.

The lift-off was normal. In five seconds, the rocket cleared the umbilical

mast. The launch pad and the jet deflector were all practically intact, requiring minimum time for the next launch. Though some events had been pre-programmed, several commands were based on real-time detection of events. The digital autopilot controlled the altitude of the vehicle during the most critical period when the rocket was subject to maximum disturbance. The onboard RESIN's measurement of the trajectory matched with that observed by the high-precision tracking radars at SHAR and Thiruvananthapuram. The telemetered chamber pressure of the third stage was found normal (Fig 5.5).

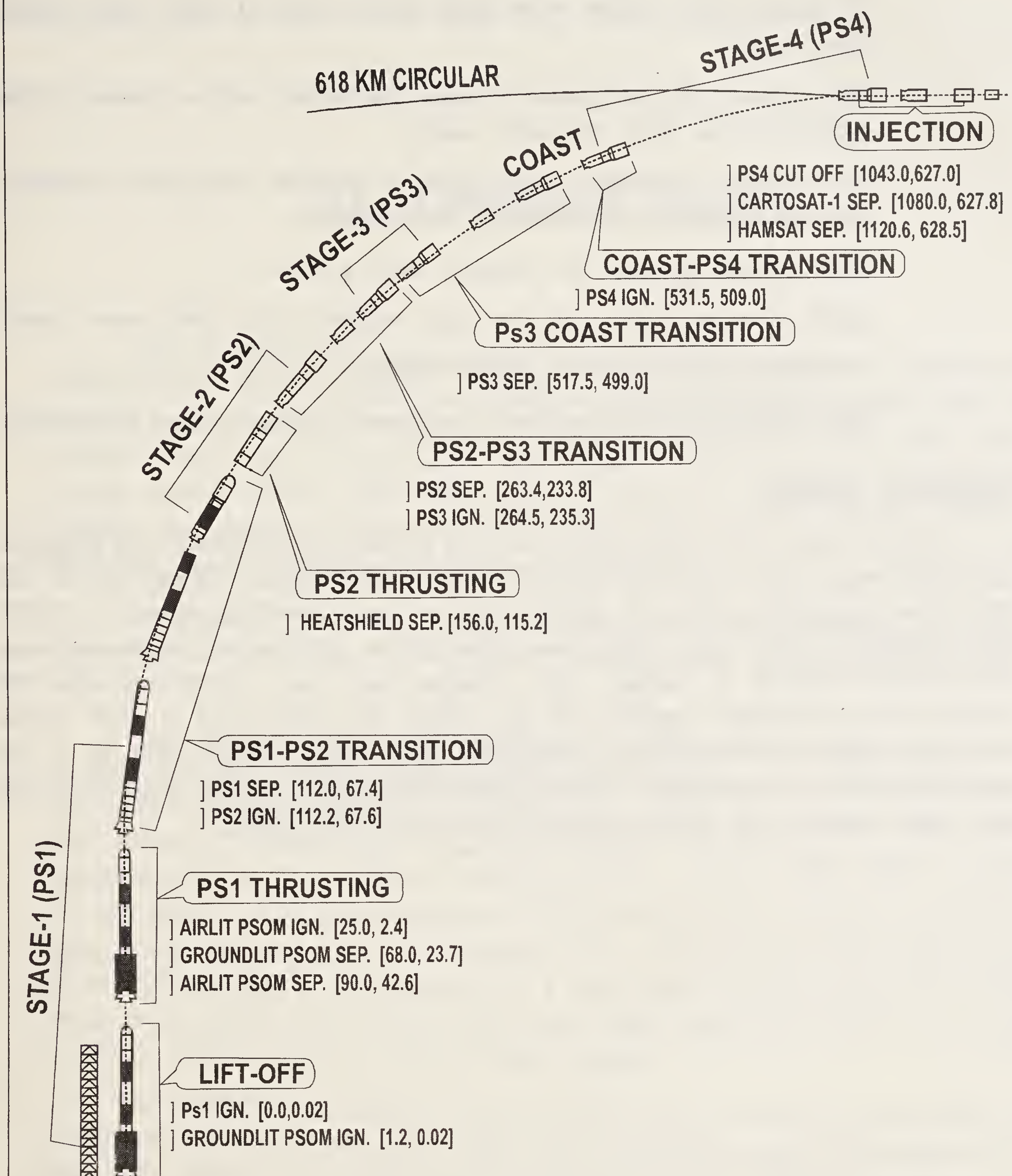
Around the second stage separation, an unexpected large disturbance occurred. It resulted in the satellite attaining an altitude of 340 km instead of 414 km by the time the third stage separated at 383.8 seconds. The velocity was only 3.54 km per sec instead of the expected 5.98 km/s. The loss of velocity and altitude resulted in a suborbital flight at about 350 km and a range of about 1,700 km along the polar flight path. Nevertheless, the fourth stage was ignited as planned; both engines developed full thrust and the engine gimball system functioned normally. The steady performance of the stage for more than 80 seconds indicated that it would have continued, if the flight had been normal. Nearly one billion bytes of data were recorded and the telemetry data were good. The telemetry data received from lift-off until 693 seconds were of high quality. The ground stations at SHAR and Thiruvananthapuram received the data. Only the station in Mauritius could not receive the data as the vehicle did not go within its visibility. An expert committee traced the failure to a software implementation error in the onboard guidance and control system.

The Failure Analysis Committee appointed to probe the failure of PSLV-D1 identified three causes. First, the time gap (3 seconds) provided between switching off the second stage engine and switching on the third stage engine, proved too much. Second, one of the retrorockets designed to pull the burnt second stage away from the third stage failed. Even then the rocket might have continued in flight but for the third reason, viz. a software implementation error, based on a wrong reading of a control parameter. Though, based on simulations, the command required to meet the worst case possible had been provided in the onboard computer, the software error led to a wrong command to the control system. Instead of correcting the error, it actually compounded it.

The shortcomings were corrected after elaborate tests.

The committee confirmed that all major systems had worked as planned and that there was no basic flaw in the design of the rocket.

Despite the failure of the subsystem, several techniques were validated through the mission:



(Numbers in brackets indicate time in seconds and altitude in km respectively)

Fig 5.5 : PSLV: Lift-off to orbit, showing stage separation.

- The giant solid booster along with six strapon motors worked in the most difficult portion of the atmosphere.
- Two liquid stages were flight-tested for the first time.

- 10 major rocket motors were flight proven and 30 other small motors were tested.
- The onboard inertial guidance system performed well as shown by the matching data from precision radars.
- Six onboard computers were linked to provide navigation, guidance, digital autopilot and sequencing of commands.
- New control systems for engines were proved.
- Light alloy structures and the large bulbous heat shield were tested.
- Pyrotechnic systems were found reliable.
- Heat shield jettisoning and stage separation systems worked successfully.

Elaborate Testing

All the stages were extensively tested on ground and evaluated. For example, the fourth stage that uses indigenously developed twin liquid engines of 700 kN thrust was extensively tested. A checkout system was specially designed for PSLV. The prototype fourth stage engine was subjected to performance evaluation tests for over 530 seconds in vacuum. (The nominal burn time of the engine is 420 seconds). The multistart capability of the engine was also tested in eight spells. A single engine was tested for a cumulative burn time of nearly 900 sec in six independent tests. A simulated altitude performance test was also conducted. The full flight version was tested except for the sea level nozzle.

12. Continued Success

The modifications recommended by the Failure Analysis Committee that identified the causes of failure of PSLV-D1 were incorporated in the rocket built for the next mission in the series. Extensive simulations were carried out for possible errors. And wider margins were given for the separation sequences than in the earlier mission. PSLV-D2 had an onboard computer-based scheme to retarget the satellite injection orbit to some extent, in case any of the lower propulsion stages performed inadequately. The mission was a complete success.

On October 15, 1994 the rocket blasted off from Sriharikota and exactly after 17 minutes placed a 804-kg IRS-P2 satellite into a near-polar sunsynchronous orbit at 820 km.

The core first stage and two strapon motors were ignited first, followed by the other four strapons 30.6 seconds later. This sequence was later changed. The strapons were separated in two stages at 73.4 seconds and 90.4 seconds after lift-off. The first stage separation and the second stage ignition occurred simultaneously at 111 seconds. The heat shield was cast off at 154 seconds at 117 km after it cleared the atmosphere. The second stage separation and the third stage firing were recorded at 261 seconds. The solid propellant third stage dropped off at 380 seconds. The rocket entered a long period of coasting over the Indian ocean at an altitude of 421 km. The fourth stage ignited after about two minutes at 591.4 seconds and cut off at 988.2 seconds.

The satellite was injected into orbit after 1012 seconds at about 817 km. The injection accuracy was quite high: 98.6° inclination against the planned 98.7°. The solar panels were deployed automatically by an onboard sequencer. The closed loop guidance on board the rocket came into effect at 157 seconds after lift-off as planned and guided the vehicle till the satellite was injected into orbit. The spacecraft was placed in a three-axis stabilized mode. The event was monitored by the Mauritius tracking station. The satellite was controlled by ISRO Telemetry, Tracking and Command Network in Bangalore, Lucknow and Mauritius. Exactly 98 minutes after the launch, the National Remote Sensing Agency (NRSA), Hyderabad received the first signals from IRS-P2. The satellite has a linear imaging self-scanner (LISS-II) camera, similar to the one flown on board IRS-

IA and 1B. Following a series of orbit manoeuvres, IRS-P2 was declared operational from November 7. The orbit was adjusted to cover a standard ground track. The perigee of the orbit was frozen (retained) at a given height.

The successful launch – the result of 12 years of hard work – marked a significant milestone in the country's space programme. ISRO had realised the full capability of guided injection of a spacecraft into orbit.

PSLV-D3: A Perfect Launch

The success was repeated by the next PSLV mission. The launch of PSLV-D3 on March 21, 1996 was described as perfect, as it traced the pre-determined trajectory from SHAR with absolute precision and injected IRS-P3, a 922-kg remote sensing satellite, into a polar sunsynchronous orbit after 17 minutes.

The launch sequence was almost similar to that of PSLV-D2. The closed-loop guidance came into effect at 157 seconds at about 117 km after the vehicle cleared the dense atmosphere. The third stage separated at 489 seconds after the blast-off as planned. The last stage ignited after a coasting period at 611 seconds. It was separated at 1029 seconds and the satellite was injected into the orbit at 1043 seconds at an altitude of 820 km. The orbit achieved - (807/816 km) had almost been predicted. The angle of inclination of the satellite was 98.88° and the eccentricity of the orbit was 0.0001 and not 0.001, as expected.

Several improvements had been carried out in PSLV-D3. One was the introduction of wind-biased trajectory to reduce the effective load on the vehicle during its ascent through the atmosphere. The trajectory was optimised after studies of the wind velocities over SHAR for about a month. Eventually an onboard guidance system, which would adjust the trajectory in real time, was proposed. Another improvement was the reduction in the mass of insulation and nozzle of the third stage by about 74 kg, and improved propellant loading. The weight of the equipment bay was also reduced by about 25 kg. The other improvements related to the PS-3/PS-4 coast phase control and the fourth stage autopilot.

The launch of PSLV-D3 validated all the modifications and marked an important step towards making the PSLV operational. The success enabled the country to realise its geosynchronous satellite launch vehicle (GSLV).

PSLV-C1

In the first operational flight in 1997, PSLV-C1, placed IRS-1D (1200 kg) into a polar orbit. The rocket has become a workhorse launch vehicle for polar satellites. The next PSLV (C2) launched Oceansat-1 (IRS-P4) in 1999 along with Korean KITSAT-3 (107 kg) and Germany's DLR-TUBSAT (45kg) (Fig 5.6).

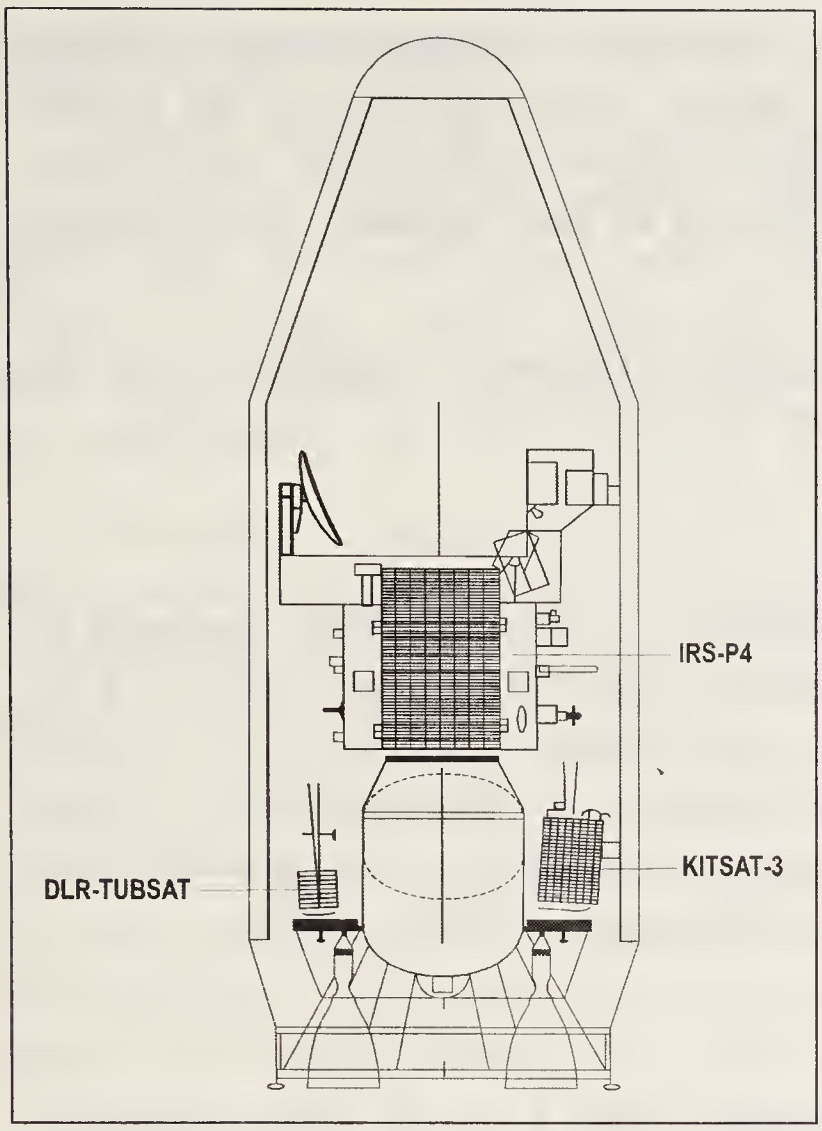


Fig 5.6 : Three satellites inside the heat shield of a PSLV.

PSLV-C3 launched a Technology Experiment Satellite (1109 kg) in 2001, together with the Belgian PROBA (94 kg) and the German BIRD (92 kg). In the next mission, PSLV-C4 launched 1,060 kg KALPANA-1, the country's first meteorological satellite into a geosynchronous orbit.

In 2003, PSLV-C5 launched Resourcesat-1 (1360 kg). PSLV-6 (2005) was the first vehicle launched from the second launch pad in Sriharikota. Though the configuration of the vehicle is essentially the same as PSLV-5, several improvements had been made, including a new propellant servicing system for the second stage called remote fill and drain, indigenous titanium for the fourth stage gas bottles, a new telemetry package, and indigenous control components for second

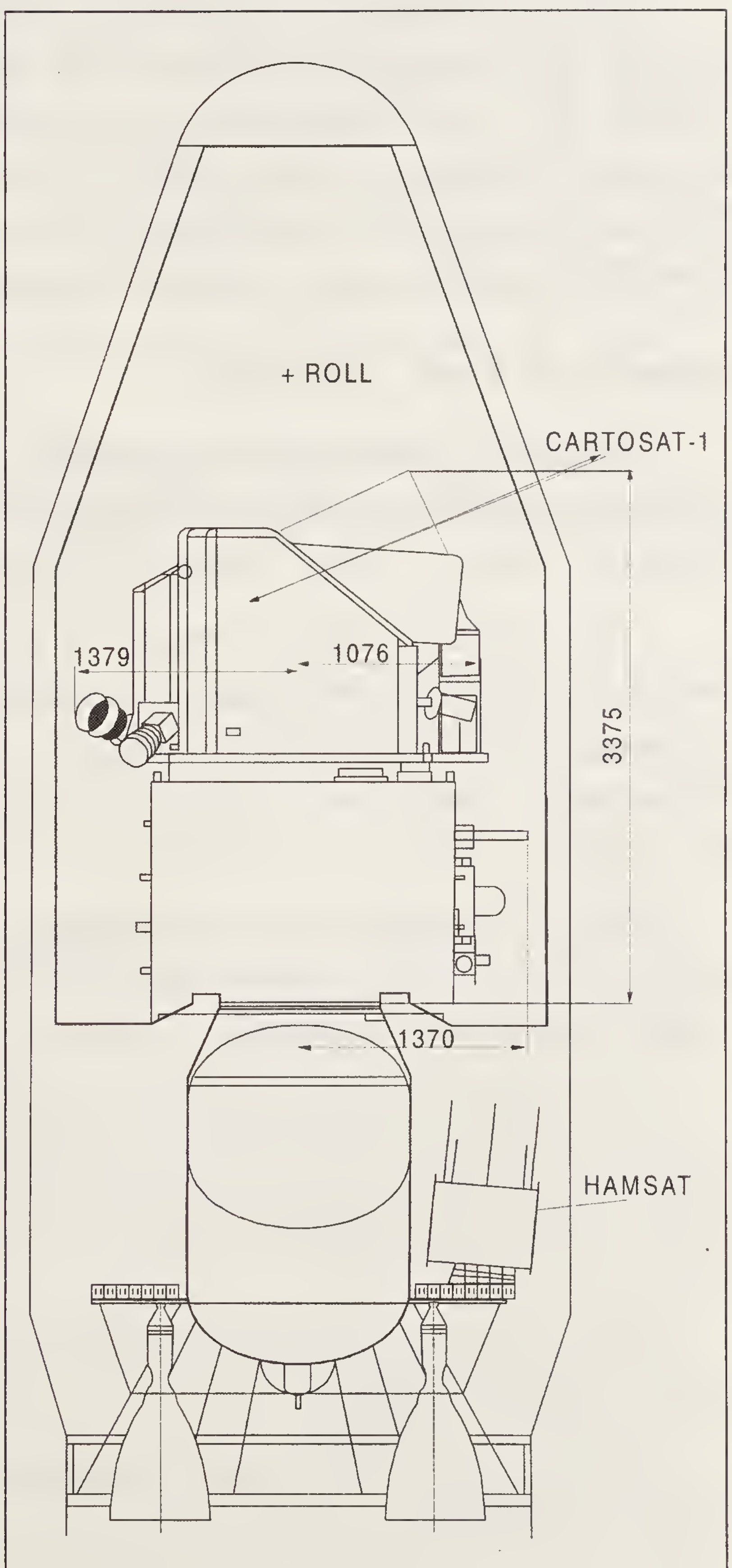


Fig 5.7 : Cartosat-1 and Hamsat were launched together.

and fourth-stages. One other change was the movement of the assembled vehicle to the launch pad, five days before lift-off, instead of the shifting of the mobile service tower, six hours before launch from the first launch pad. The rocket remained on the launch pad for five days, exposed to rain, thunder and lightning, but without any adverse effect.

PSLV-6 carried the heaviest remote satellite (Cartosat) weighing 1,560 kg as against the 804 kg IRS-P2 in 1994, and HAMSAT (43 kg) (Fig 5.7).

HAMSAT : Widespread Use

A co-passenger of Cartosat-1 was HAMSAT, a micro satellite designed to provide radio amateur services to the international HAM community. The 43.5 kg satellite has two transponders, one Indian and another, designed by a Dutch amateur operator from the Higher Technical Institute in The Netherlands. More than a thousand users including doctors, engineers, members of the armed forces from 50 countries have reported excellent performance of the satellite.

Launch of Four Satellites

PSLV-C7 launched four satellites: Cartosat-2 (680 kg) and Space Recovery Experiment (SRE) of ISRO, weighing 550 kg a 56-kg Indonesian satellite (LAPAN-TUBSAT), and a 6-kg Argentine satellite, Pehuensat-1.

The mission had the benefit of several improvements: more propellants were loaded into stages motors; use of composite materials for satellite loading structures; a change in the sequence of firing of the strapon motors; less propellant in the fourth stage; and video imaging to record the separation of the dual adaptor from the payload, which was carried for the first time.

The first stage with six strapons is one of the largest solid boosters in the world (138 t). The second stage uses liquid propellants (41.5 t), the third has a solid motor (7.6 t) and the fourth stage has a twin engine 2-tonne liquid motor.

In order to lift heavier payloads (e.g. Chandrayaan-1 and RISAT), an improved version of the solid propellant strap-on motor (PSOM-XL) has been static tested. The improved rocket is designed to lift 1,600 kg, as against 1,450 kg at present.

A satellite of Singapore's Nanyang Technical University (100 kg) is scheduled to be launched soon.

PSLV has proved several systems that are used in geosynchronous launch vehicles (GSLV).

Without Strapon Motors

A PSLV without the six strap-on motors was successfully launched in 2007 to put an Italian astronomy satellite, called Agile. The orbit achieved was also different from the usual polar orbit designed for resource satellites. Agile was put into a 550 km circular orbit above the equator with an inclination of 2.5 degrees to the equator so that it can observe the celestial sources of X-rays and gamma rays.

The satellite weighed 352 kg and along with it ISRO launched an advanced avionics module, weighing 185 kg, to evaluate innovative technologies for navigation and stability. In view of the less weighty payloads, the propellant in the fourth stage was reduced by about 400 kg. The core of PSLV-C8 as the mission was called, had a lift-off mass of 230 tonnes, which orbited a total of 537 kg. The mission was perfect and the the satellite was in orbit in about 22 minutes. Agile was the first major commercial launch and the Italian scientists who witnessed the launch were all praise for the high professional way the mission was planned and implemented. Since 1994, the PSLV has launched eight satellites and six small satellites for foreign clients as of April, 2007.

The PSO motor is being upgraded by adding three tonnes of propellant to gain an additional payload capability of 150 kg in a 600-km polar orbit.

The Road Map

The PSLV road map for the next decade is a challenging task with a target of launching 10 satellites. They include: a radar satellite; ASTROSAT, Chandrayaan-1 and Oceansat-2. The success of the PSLV has resulted in several joint ventures between ISRO and foreign space agencies.

A World Player

A review of ISRO's recent international co-operation activities shows two remarkable features: Indian expertise in making and launching satellites is valued highly worldwide and its scientific know-how in exploring science is also held in high esteem by the international scientific community. India's capability in meeting new scientific and technological challenges in space is widely recognised.

The United States has shown support for enabling the launch of US licensed satellites from India. The USA has taken steps to allow exports to several ISRO units with less red tape. A joint working group between the two countries has been formed to improve high technology trade between them. US scientists too recognise the world-class work

Contd...

done in India. Accordingly, two guest payloads of scientific instruments will be on board India's lunar probe, Chandryaan-1.

Russia has been a long-term ally of India in launching its satellites in the early days of ISRO. Russian cryogenic engines power the initial series of India's GSLVs. India is closely co-operating in the development and use of the Russian GLONASS navigational satellite programme. India may launch some of the satellites for the Russian network. GLONASS would be a useful supplement to the US-operated GPS system for location and guidance in navigation. An Indo-Russian YOUTHSAT is being planned for the benefit of university students of both countries.

It has been announced that a Russian satellite for the study of the solar-terrestrial interactions will carry an Indian scientific instrument. India has a long tradition of solar observations starting from the Kodaikanal solar observatory.

A joint mission with France, Megha Tropiques would study the tropical atmosphere and climate-related aspects such as monsoons and cyclones. ISRO and the French Space Agency (CNES) would jointly develop an instrument called MADRAS. An Indian remote sensing satellite will fly this and other payloads using a polar satellite launch vehicle (PSLV). ISRO will operate the satellite as well as collect and distribute the data. In addition, Oceansat-3 of ISRO will carry a radar altimeter (which will help measure the height of the sea surface) provided by CNES. Oceansat-2 will include an atmospheric sounder called ROSA from the Italian space agency.

ISRO and the Canadian Space Agency are working on an ultraviolet imaging telescope to be carried on board India's mutiwavelength astronomy satellite, ASTROSAT. Three ultraviolet telescopes of Israel's Space Agency and the Tel Aviv University will be included in the payload of GSAT-4, ISRO's experimental geostationary satellite.

In a significant deal, a leading private company in Europe, EADS Astrium, Paris, has entered into an agreement with ANTRIX, ISRO's commercial arm, for joint manufacturing of two to three tonne satellite platforms for the world telecommunications market. It will offer cost-effective and optimal solutions to telecom operators. EUTELSAT, Europe's largest satellite communications operator, has given the commercial export contract to the joint venture.

Oceansat-2 has an Italian sensor developed by the Italian Space Agency. Called Radio Occultation Sounder for Atmospheric Studies (ROSA), it will help in identifying fishing zones, sea state forecasting and weather and climate studies.

ISRO has signed memoranda of understanding with 23 countries including Australia, Brazil, China, Germany, Japan, Russia, Sweden, Thailand, UK, Ukraine and Venezuela, besides EUMETSAT and ESA.

A leading training centre for space science and technology education for Asia and the Pacific has been functioning in Dehra Dun for the last 10 years. It was set up in India at the initiative of the UN Office for Outer Space Affairs. The Centre offers courses in remote sensing and geographical information system, satellite meteorology, satellite communication, and global climate and atmospheric studies. Scientists from developing countries get training under a scheme called Sharing of Experience in Space.

India is an important member of the Satellite-aided search and rescue operation by an international programme for providing distress alert and position location service through low earth orbit search and rescue satellite system. Indian local user terminals will provide coverage to a large part of the Indian Ocean region. The INSAT system also detects the distress alert from ships that are adrift.

In the field of remote sensing data on natural resources, several countries including USA and Russia regularly receive data from Indian satellites under commercial arrangements. There are 24 ground stations in various countries that receive data from IRS satellites directly. The Indian data products are not only technically world-class but also cost-effective. ISRO's commercial wing, ANTRIX, markets the products and services.

When the first sounding rocket was launched from Thumba in 1963, India offered the advantages of its geographically significant location for conducting space exploration in the upper atmosphere. Today, India continues to offer technological and scientific advantages to all nations planning space technology for applications and exploration for peaceful purposes.

The International Astronautical Congress - 2007 was held in Hyderabad.

Permanent Facilities

Several major facilities were set up for PSLV; they are useful for various missions including geostationary SLV. The facilities include sea-level and high-altitude test facilities at Mahendragiri for qualifying the second and fourth stage liquid engines, fabrication facilities to deal with large diameter (2.8-3 m) rocket hardware, titanium machining and welding as well as production facilities for propellants, propellant casting and curing. There are also facilities for qualifying massive light alloy structures and heat shields for testing inertial sensors and simulation of the entire mission including testing of stage separation and heat shield jettisoning. A mobile service tower at SHAR and a launch control centre and radars at SHAR and Mauritius have also been provided. The major responsibilities for the design and development of PSLV were shared by VSSC, the Liquid Propulsion Systems Centre and the SHAR Centre. The ISRO Inertial Systems Unit developed the guidance and navigation system. The ISRO Telemetry, Tracking and Command Network was in charge of telemetry and tracking support.

RADAR Development

Radars are indispensable for tracking launch vehicles and ensuring range safety in case the rockets deviate in an undesirable direction. From lift-off to injection into orbit, a radar tracks the rocket every 100 millisecond (as in a PSLV) up to 800 km.

The first radar at Sriharikota was ready in 1975 well before the launch in 1979. SLV-3 was not a fully guided rocket. It was guided by onboard devices up to the third stage only. In contrast, PSLVs and GSLVs have inertial navigation systems (INS) on board and autonomously guide the rocket. Even so, radar is essential because in case of a malfunction of the rocket, the INS may not be depended upon, as it happened during the failed GSLV mission, when the deviating rocket had to be destroyed on ground command.

A tracking radar is different from a scanning radar (as in an airport). The former follows a target rather than merely detect it. The tracking radar is based on the detection of the shift in frequencies with which the energy of the reflected signal from the target is received, known as the Doppler shift.

Three generations of tracking radars of ISRO have been developed. The second was transportable, while the third was more accurate than the others in locating the target. The radars have supported the launch missions from SLV-3 to GSLV. The angular accuracy in locating a target has improved from 0.05 degree to 0.005 degree. The latest version is called precision coherent mono pulse C-band tracking radar (PCMC). What this rather long jargon means is simply this: unlike the older generation radar where the error in locating a target was calculated

on the basis of every four pulses sent out, the mono pulse radar, as the name implies, processes the error of every pulse and thereby resolves the error more accurately. When a target is on the axis of the antenna, the error is zero. But when the target is moving fast like a rocket, the error is inevitable and the attempt is to minimise it. That is how 0.005 degree error or less is aimed at. The vertical (elevation) and horizontal (azimuth) angles of the radar and the movement of its parabolic dish are all calculated in arriving at the error. The slant range of the radar is up to 3,000 km. Two tracking radars are in Sriharikota. The PCMC radars were jointly developed by ISRO and Bharat Electronics.

If the altitude of the target is below 300 km at the perigee of the geosynchronous transfer orbit, it will not be in the line of sight of a ground radar because of the Earth's curvature. That is why a monitoring station is set up in Biak in Indonesia from where it is possible to watch a GSLV inject a satellite into the transfer orbit. For monitoring the injection of a satellite by a PSLV which occurs over Mauritius, a radar was set up there, when the onboard INS was not fully developed.

When a radar receives a signal from a target like the rocket, the atmosphere attenuates the signals in both directions. In order to overcome this problem, a transponder is kept on board the vehicle in space, which gets a megawatt beam and retransmits it at a slightly different frequency but with a power of 400 watts. The tracking range can then extend to 4,300 km and beyond.

A next generation radar is being developed with more software and computer-controlled technology. It will have a digital storage of radar video and real time display and will have completely automatic tracking facility. The new radar, under production by Larsen & Toubro, a private firm, will be used for the launch of the next generation of GSLV rocket (Mark III).

The knowledge base of ISRO's Radar Development Unit (ISRAD) is used for developing atmospheric and weather radar systems. In collaboration with the India Meteorological Department, ISRAD has designed, developed and commissioned a Doppler Weather Radar. It is a state-of-the-art system which can provide advance warning of severe weather including cyclones, some 500 km away. A total of some 60 such radars are proposed to be installed in various parts of the country.

It is also planned to install a wind profiler at SHAR to get a 3D view of the winds every 100 metres up to a height of 20 km, just above the troposphere. At present a wind profile is obtained by instruments sent up in balloons just prior to the launch of a rocket. The wind profiler will capture the dynamics of the atmosphere better.

The study, of the dynamical processes by determining the 3D wind vector is being done now at the MST (Mesosphere, Stratosphere and Troposphere) radar at Gadanki near Tirupati. The radar estimates atmospheric winds with very high temporal and spatial resolution continuously. The beam steering and data acquisition are computer-controlled.

The evaluation of new materials and subsystems continues as a regular activity. Several test facilities have been established in Thumba and Sriharikota as the sophistication of the systems increased. Scale models of rockets and satellites are tested in wind tunnels where wind speeds exceed that of sound (1216 kmh). The effect of ground wind on a rocket is studied with the help of scale models. Loads and pressures likely to be experienced by the rocket motors are simulated and parts tested. For example, the load on fins and how they are affected by air flows are ascertained.

As a rocket motor burns, it vibrates and produces noise. Their impact on the stability of a rocket needs to be evaluated. A vibration test facility in Sriharikota evaluates the upper stage motors, satellites and their subsystems by simulating the vibration environment. Samples can be subject to a force of 100 g. (The Earth's gravity exerts a force of one g.)

A launch vehicle experiences shocks at various stages, particularly during lift-off and stage separation. The impact of shock is studied in ground tests.

Motors of sounding rockets are fired on the ground to test their systems. They include jettisoning of nose-cones or fairings so as to expose the scientific payload at the appropriate altitude.

For qualifying upper stages of rockets and some of the subsystems, the constant acceleration facility at Sriharikota is used. It can simulate acceleration of 25g for a specimen weighing 1000 kg or 10 g for an object weighing 2,500 kg.

The thrust and other parameters such as temperature, pressure and vibration are measured during the firing of rocket motors at sea level conditions. It is called static test, where the rocket does not go up. A special test facility enables the engineers to study how a rocket motor will behave.

Another feature simulated is heat. High-powered xenon lamps create the needed heat for testing the subsystems. The separation of heat shield and stages without damage to the rest of the vehicle is also tested.

High Altitude Test

One of the most difficult simulations of natural conditions is creating vacuum to test the behaviour of stages and rocket motors above the atmosphere.

A high-altitude test facility has been set up in Sriharikota. Creating the facility for a solid propellant motor proved to be quite a challenge. The simulated conditions inside the facility should be equivalent to vacuum at an altitude of 50 km. The vacuum is maintained for 400 seconds during the test. The apogee boost motor for APPLE was tested in the facility before it was flown. The rocket exhaust is ejected by the steam generated nearby. The thrust and the burn time of the motor, whose incremental velocity pushed APPLE into the planned higher orbit, were measured. The facility is useful in assessing the performance of new motors, their thrust levels and new types of expanded nozzles.

Simulation by Computer

The most fascinating simulation is the creation of conditions in a launch vehicle under control and guidance. The interaction of the various commands put out by the onboard computer and the response of the vehicle and subsequent decisions of the computer are recreated accurately and what is more, they can be simulated in real time. This is achieved by a hybrid computer.

A hybrid computer is a happy marriage of digital and analog computers. While the more commonly used digital computer deals with numbers, an analog computer represents numbers by equivalent positions on a scale. The digital computer is precise, but rather slow. The analog computer, in contrast, is not very precise and has a poor memory but is very fast and is easier to interact with. A combination of the two will result in speed, accuracy, memory and good interaction.

A hybrid computer can create exactly the same electrical signals as would occur in actual flight. The electrical signals can be fed to the rocket's autopilot, inertial measurement unit and other control and guidance systems. Using actual systems and simulating commands for them is called hardware-in-loop simulation. This is essential before advanced computer-based guidance systems are flown in ASLV and PSLV missions. The simulation in real time can be usefully done for testing particular subsystems such as liquid engine design, strap-on techniques and separation systems.

Ensuring reliability of the components is crucial to the success of a mission. Even small errors can develop into major snags. Quality assurance therefore starts right from the conceptual stage and continues till the operational phase.

In a related field (but not in collaboration with ISRO), missiles for self-defence were designed and developed by the scientists and engineers of the Defence Research and Development Organisation of the Ministry of Defence.

Missiles for Self-defence

While ISRO produces rockets for launching satellites that provide communication, data and television links to the country besides monitoring the weather, the Defence Research and Development Organisation of the Ministry of Defence designs, develops and produces a series of missiles for self-defence under the Integrated Guided Missile Development Programme. Started in 1983, four missile systems viz. Prithvi, Trishul, Akash and Agni have been developed and tested. A recent addition is Brahmas (derived from Brahmaputra and Moscow), made with Russian collaboration.

Prithvi is a ballistic missile. A ballistic missile is guided in the first phase of its flight but is allowed to fall freely as it approaches the target, when the thrust is switched off. In contrast, cruise missiles are continually powered and guided.

Prithvi is a short-range surface-to-surface battlefield missile. It has a single stage liquid propulsion system. The army version of the missile has a range of 150 km and it can take a one-tonne payload under inertial guidance. The missile's trajectory can be changed in real time. The Air Force version has a 250 km range. A Navy version, called Dhanush, which has a range of 350km, had been test-fired. Another version, Prithvi-III, can be fired from the ground, vehicle or ship.

Agni is an Intermediate Range ballistic missile. Agni-I has a solid propellant booster and a liquid propulsion upper stage. It has a short range of 800—900km. Agni II is a two-stage, all solid propellant system with a range of over 2,500 km. Its re-entry into the atmosphere can withstand a temperature of 3000° Celsius at hypersonic speed of 12 to 14 Mach number. It needs a supercomputer and advanced radar for multi-target tracking. Agni III, a surface -to -surface missile has been successfully test-fired. In April, 2007 the two-stage solid propellant ballistic missile was launched from an island off the coast of Orissa. The fully indigenous missile, weighing 48.3 tonnes, can take a 1.5 tonne payload including a nuclear warhead. The missile has a range of 3.500km. The successful test proved the re-entry technology and other advanced systems that provide automatic guidance. The missile went up to an altitude of 400km before plunging into the Bay of Bengal at a preset point in a ballistic descent.

Akash is a medium range surface-to-air missile with multi-target engagement capability. It operates under radar homing guidance with

high accuracy. It can deploy missiles to attack four targets at the same time within a range of 25km.

Trishul is a surface-to-air missile, which can be fired from a moving vehicle. It can also be used as an anti-sea skimmer from a ship against low-flying missiles. It can counter all known aircraft jammers. It uses high- energy solid propellants. It will be a boost to mobile armoured columns.

Nag is a third generation anti-tank missile system, which can destroy battle tanks. Nag can be fired from a tracked vehicle or helicopter.

In December 2007, an intercepter missile (single stage with solid propellant) of DRDO scored a direct hit and destroyed a target missile over the Bay of Bengal at an altitude of 15 km in its very first attempt. Later, an Akash missile destroyed a moving target in the air, about 20 km away.

An Indo-Russian joint venture, BrahMos Aerospace, has been formed to produce different versions of BrahMos, a supersonic missile. It can be flown both horizontally and vertically. The missile can attain 2.8 –3 Mach speed at a height of 15km. It can be launched from anywhere—silos, mobile platforms, ships, submarines and aircraft with no design changes. It can deliver a warhead of 200 to 300kg within a range of about 300km. A surface to surface version is operational. It is a two-stage missile, with a solid propellant booster and a liquid propellant ram jet system, with anti-jamming devices.

The Navy has fitted a BrahMos in its warships. The missile can be fired from a mobile or fixed platform on land, from a ship or from a subinarine or a warplane. The range is 300km, which is within the limits set by the Missile Control Technology Regime Treaty. The missile is supersonic (over 2 Mach) and its flight range is thrice more than a subsonic missile.

An air-launched version of BrahMos is under development. It will be integrated with the fighter aircraft, Sukhoi-30 MKII. The Army will also get the missile soon.

PART - VI

GSLV: MEETING THE CHALLENGES

13. The First Launch

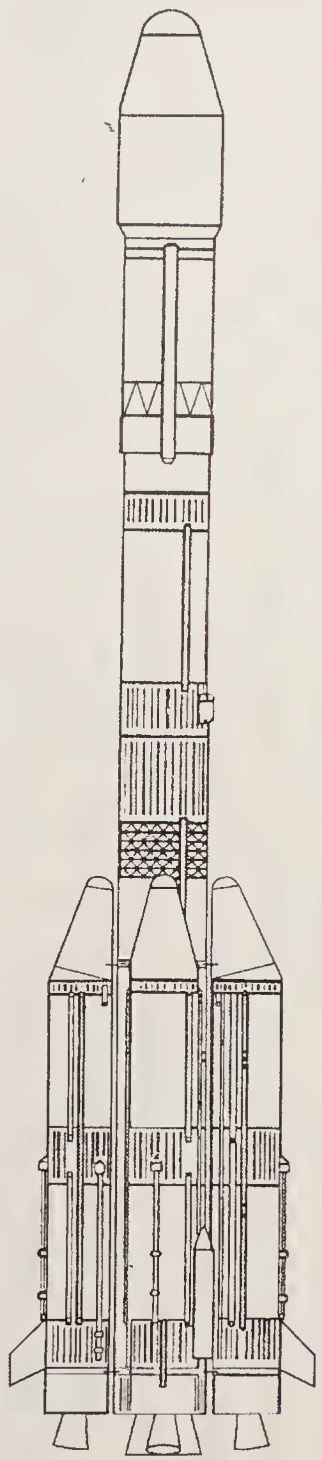
The specific impulse of the cryogenic propellant is of the order of 450 sec., compared with liquid and solid propulsion, which gives only 300 sec. For every one second gained in the specific impulse, a payload gain of 10 kg is possible. It is enough to use cryogenic propellants in one stage of the rocket, provided the other stages are sufficiently powered by Earth storable liquids as well as solid propellants. In the Indian geostationary SLV (GSLV), the core solid propulsion-based first stage and the liquid second stage are the same as used in a PSLV, while the its six solid strapons are replaced by four liquid strapons and the third and fourth stages (Fig 6.1).

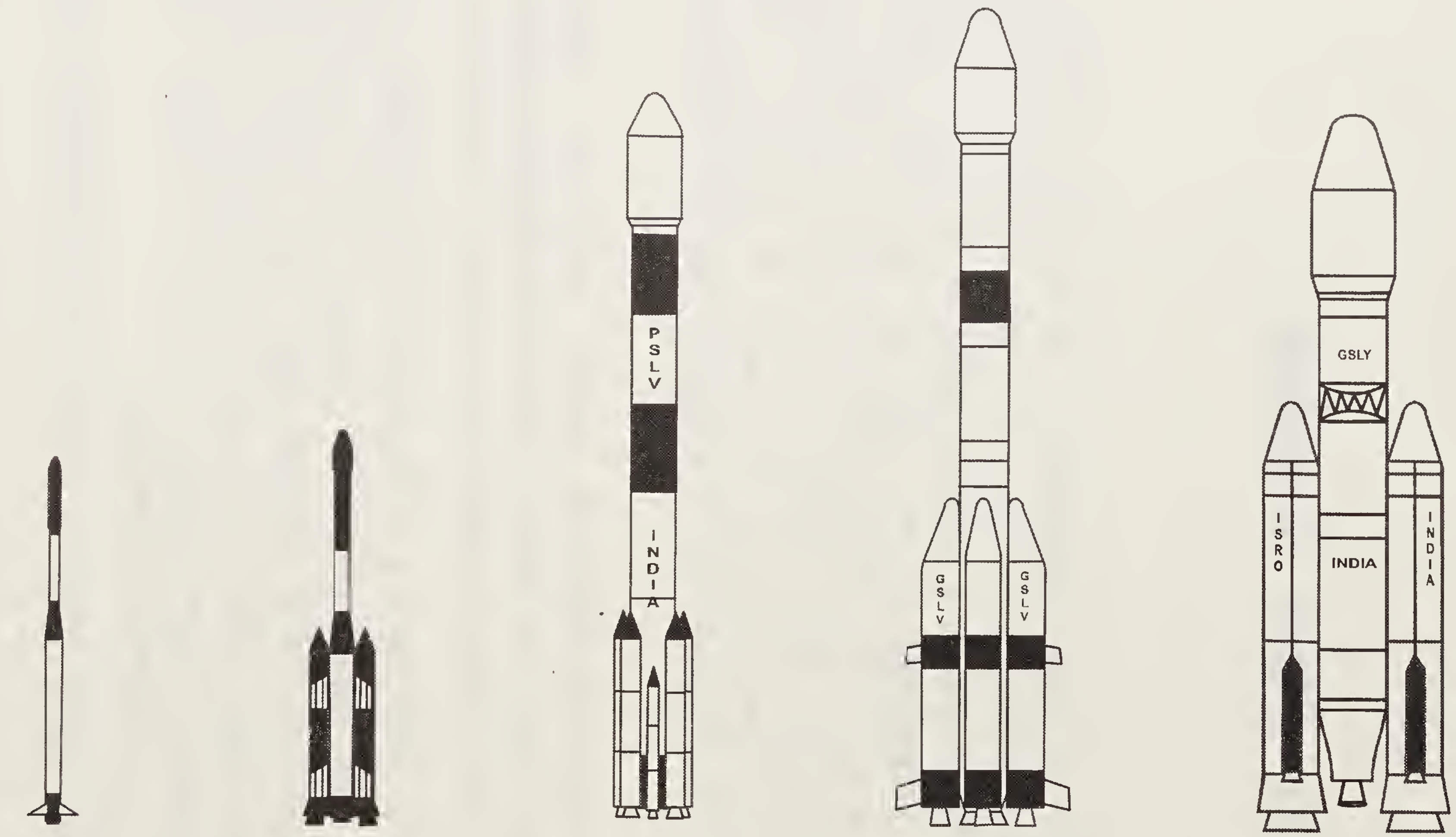
INSAT-1 weighed 1200 kg and INSAT-2, almost 2,000 kg. Typically, geostationary payloads nowadays need 2.5t. Hence the most efficient method of reaching the orbit is preferred. And that is based on cryogenic propellants.

The first stage of GSLV-1 will have a 129 tonne solid propellant motor similar to that of PSLV, with four liquid propellant strapons each carrying 40 tonnes of propellant, derived from the PSLV second stage. The second stage of GSLV will be a liquid propellant stage with 37.5 tonne of propellant as in PSLV. The third stage's restartable cryogenic engine carries 12 tonnes of liquid oxygen and liquid hydrogen with a 3.4 m diameter heatshield.

A high efficiency cryogenic upper stage is chosen for geostationary launch vehicles.

The first developmental flight of GSLV was attempted on 28 March, 2001. In the final moments of the countdown, the onboard computer had taken over control. The strapon motors had been ignited and three seconds later, the computer halted the launch sequence. It was only one second to go before the big solid rocket was to ignite. Had it ignited, it could not have been stopped and the mission would have ended in a disaster. It was later found out that the computer had switched off the sequence just 4.2 seconds to zero in the countdown, as it sensed that one of the strapon motors was giving low thrust. An insulation on one of the strapons had caught fire, which was put out by the equipment provided. The rest of the rocket was saved. It was detected later that defective plumbing in the oxidiser flow of the engine was the cause of the low thrust.





	SLV	ASLV	PSLV	GSLV MK-1 and 2	GSLV MK-3
Height	22m	23.5m	44.53	49m	42.4m
Weight	17 tonnes	39 tonnes	294 tonnes	414 tonnes	629 tonnes
Fuel	Solid	Solid	Solid & liquid	solid, liquid & cryogenic	solid, liquid & cryogenic
Payload weight	40 kg	150 kg	1400 kg	2000 kg	4000 kg
Orbit	Low Earth (300-900 km)	Low Earth	Polar synchronous	Geostationary	Geostationary

Fig 6.1 : India's geostationary satellite launch vehicle has a solid propellant core first stage with four liquid propellant strapons, and a liquid second stage (the same as used in a PSLV) but a cryogenic third stage. GSLV is shown with other ISRO rockets.

The technical snag was corrected within a short period. The defective strapon engine was replaced. The launch took place on 19, April 2001. It was successful. However, the satellite's orbit was less than ideal, the height of the highest point of the satellite it carried (GSAT-1) was less by 3,800 km. It was later traced to underperformance of the third stage. The velocity was some 79m per second less. The Master Control Facility at Hassan later fired the onboard apogee engine to correct the orbit.

GSLV's experimental satellite, GSAT-1, weighing 1540 kg was designed to prove new elements such as fast recovery, star sensors and ten Newton reaction control thrusters. It had two C-band transponders for demonstrating digital audio broadcast, Internet services and compressed digital TV experiment.

The second development flight of GSLV, with GSAT-2 on board weighing 1825 kg was launched successfully in 2003. The additional weight was possible because of enhanced propellant loading in the core of the first stage and use of a high-power engine in the liquid propellant strapons as well as in the second stage, besides some structural improvements.

14. A Perfect Launch

The first operational flight of GSLV was a text-book launch. The rocket placed the geosynchronous satellite, EDUSAT, in the correct transfer orbit. Though weatherman predicted rain in the Chennai area on the eve of the launch, few expected a heavy downpour on the day before the launch on September 20, 2004. ISRO did not want to take chances. It sent up a balloon to verify the winds in the upper atmosphere at about 20 km. A radar developed by ISRO was also used. The trajectory was fine-tuned in accordance with the wind data. The strategy was called zero angle of attack, which simply means avoiding undue resistance to wind forces.

This was an essential work away from the limelight. For, the edge of the troposphere at about 16km can play havoc with a rocket. It may be recalled that in 1988, ASLV-2 encountered unusually high winds and gusts, which compounded the inadequacy in the control systems, preventing its strapon rocket from separation.

This time at half past nine in the morning, the rocket was cleared for launch. It was noteworthy that the countdown did not have a single hold. Still, as the countdown was nearing its end, tension mounted. Many who gathered to witness the launch mumbled a line or two in prayer and all eyes were fixed on the spot where the rocket would rise from the ground. At 4. 2 seconds to zero in the countdown, the four liquid rockets of the first stage, each with 40 tonnes of hypergolic fuel (propellants that burn spontaneously when mixed), started burning and performed flawlessly, and the 138t first stage ignited and rose majestically above the ground.

As a rocket's thrust at ground level should be more than the total mass of the rocket including the payload, the first stage and its four strapons together produced 7,952 kilo Newton thrust to lift a weight of 414 tonnes, resulting in a high thrust-to-weight ratio. (A mass of 102 grammes – the weight of an apple (!) — is roughly equivalent to one Newton).

It was a sight for the gods as the steady flames gushed out from the leaping rocket, with a loud boom breaking the silence. As the vehicle disappeared into the sky, media persons rushed down to watch the big screen displaying its

further progress. The first stage burnt out as planned at 104 seconds, the strapons at 150 seconds, when the second stage took over, followed by the separation of the heat shield at an altitude of 115km and 227seconds into the flight. The second stage burnt out at 288 seconds. This was followed by the ignition of the cryogenic third stage at 304 seconds and its shutdown at 999 seconds, giving the required velocity. At 1,014 seconds EDUSAT was put into orbit. It was then 5000 km away from Sriharikota, over Indonesia. The separated cryogenic stage was reoriented so as to avoid any collision with the satellite (Fig 6.2).

The velocity of the satellite at injection into the orbit was 10.2km a second as planned. If it were 11km a second, the orbit would have been an ellipse and at 7.9 km the orbit would have become circular. The satellite's solar panels were deployed shortly after it was in orbit. All the sequences went off as planned. The satellite was monitored by the ground stations at Biak in Indonesia (set up by ISRO), in Canada, Italy and Beijing, besides the Master Control Facility in Hassan (Karnataka) and the ISRO tracking network in Bangalore.

The launch was unbelievably perfect. The significance of the success could be truly appreciated, when one recalls some of the notable failures of rockets abroad. On 6, September, the third stage of the Israel's booster malfunctioned and the launcher plunged into the sea, taking with it a spy satellite. In November, 2003, the Japanese H2A rocket failed minutes after lift-off, as one of the two boosters did not detach. The Mission Control destroyed the rocket, signals from the rocket under the sea were later detected. In December 2002, an Ariane rocket of the European Space Agency exploded at three minutes into the flight, destroying its satellites on board. In July 2001 an Ariane had a propulsion failure of its upper stage, attaining a maximum velocity of 8 km a second instead of 9km resulting in a wrong orbit for the satellite. The first GSLV's third stage underperformed (in 2001) resulting in a slight reduction in the velocity of injecting the satellite into orbit, which lowered the apogee (the farthest point from Earth) by 3800km.

These examples show that even the best rockets could fail and one cannot be sure of complete success all the time. The learning curve is hard and costly in this business. And so nothing is left to chance as far as possible. Not all tests can be made on the ground though. Still as many as 3, 000 simulations are done for a GSLV. Also, three-axis sensors ensure accuracy of the rocket's path along the pitch, roll and yaw directions within a fraction of a second. There is also what is known as the event management computer system onboard for correcting deviations. Moreover, GSLV has the world's best propellants (made in India). GSLVs in the near future will use indigenous cryogenic stage and engine propelled by liquid hydrogen (at -252° C) and liquid oxygen (at -183° C).

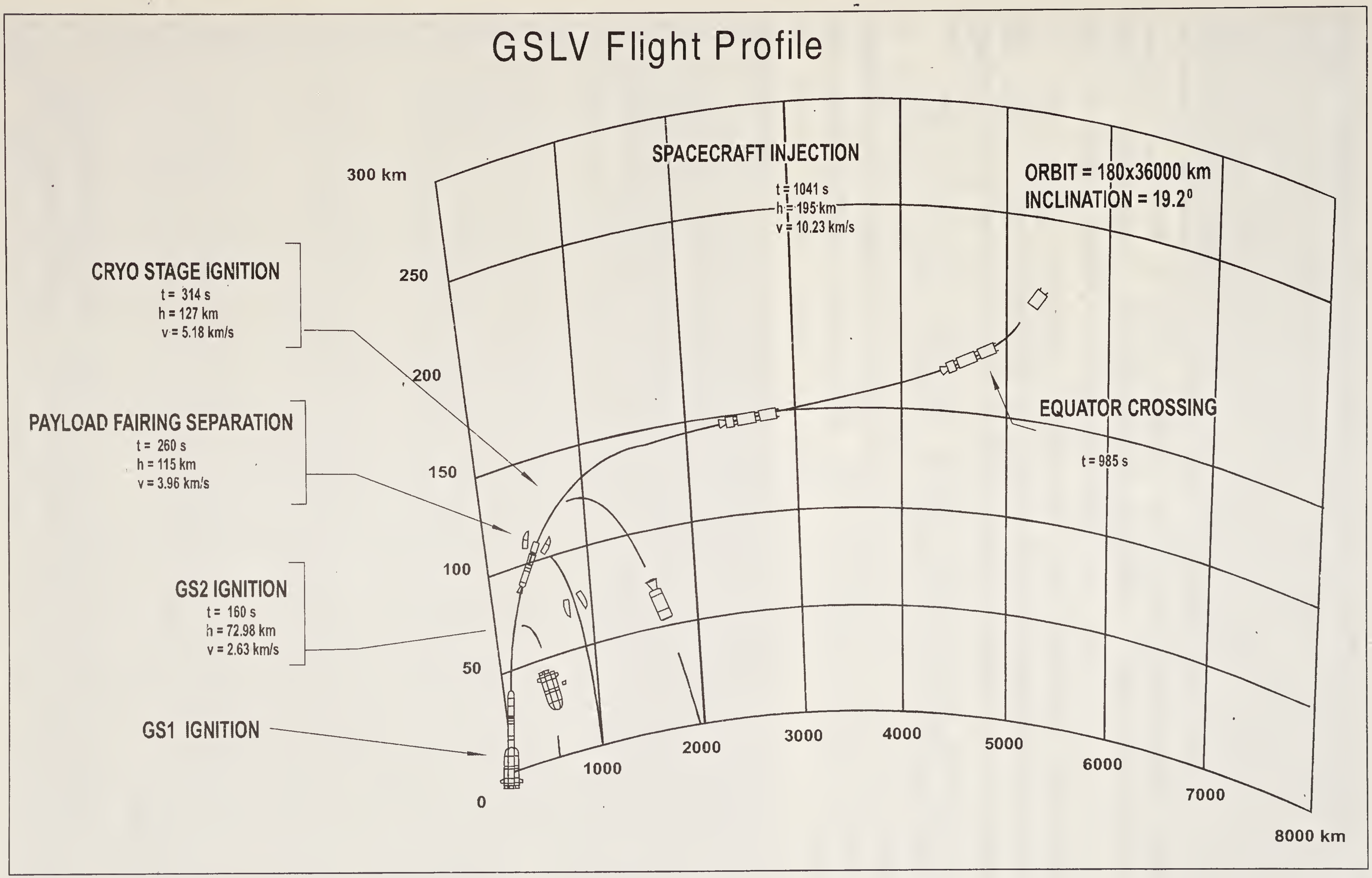


Fig 6.2 : Flight Profile of a GSLV. Displays time, height and velocity of the rocket from launch to orbit.

The egg-shaped transfer orbit into which EDUSAT was injected had a perigee of 180km and an apogee of 35,985km. Subsequently, the Master Control Facility (MCF) at Hassan raised the perigee in stages by firing the onboard apogee boost motor on three days for a total of 94 minutes after precise calculations to add an additional velocity of 1. 66 km a second and make the orbit circular and near- geosynchronous with almost zero inclination to the equator. The satellite started drifting towards its allotted position at 74 ° East longitude to be colocated on October 2 with Kalpana and INSAT-3C. At the height of about 36,000 km above the equator, the satellite appeared as a fixed star, as its speed synchronised with that of the Earth. The satellite's three-axis stability system was switched on, with momentum wheels running at 4,500 revolutions a minute. One more good news was that the satellite is likely to function throughout its designed life of seven years, as it was left with 300 kg of fuel, (out of 1128 kg it had at the beginning of the orbit), adequate for corrections during the period.

ISRO proved that it is on par with global players in launching geosynchronous launch vehicles, placing satellites into the correct orbit and maintaining them accureately.

The Three Stages of GSLV

GSLV is a three-stage rocket, 49m tall. The core first stage motor and the second stage were derived from PSLV's first stage solid propellant motor and the liquid propellant engine, respectively. The strapon motors of the first stage of GSLV were also derived from the second stage of PSLV.

The first stage of GSLV has 129t of HTBP-based solid propellant motor and four liquid propellant strapons as against six solid propellant strapons in the PSLV. The solid motor stage of the GSLV is 20.3m long and 2.8 m in diameter. Each of them holds 40 tonnes of hypergolic fuel (UDMH and N2 and O4).

The second stage is 11.6m long and 2.8m in diameter. It carries 37.5 tonnes of UDMH and N2O4. The engines used for the strapon motors and the second stage are similar.

The third stage has a cryogenic engine procured from Russia. It uses liquid hydrogen and liquid oxygen as fuel and oxidiser, respectively. The stage is 8.7m long and 2.8m in diameter. It carries 12.5tonnes of propellant.

In terms of thrust, the first stage develops 4700 kiloNewtons for 100 seconds. Each of the four strapons and the second stage have 680

to 700 kiloNewton thrust. The strapon burns for about 160 seconds, while the second stage burns for 150 seconds. The third stage produces a thrust of 75 kiloNewtons for about 750 seconds. Even as ISRO uses the Russian engine and the stage, their indigenous versions are getting ready.

New features of GSLV include an improved inter-stage between the first and the second stages. It will facilitate the firing of the second stage even as the first stage completes its thrusting action.

The control and guidance, telemetry and tele-command are placed above the equipment bay. A heat shield (larger than in the PSLV) protects the vehicle electronics and the spacecraft during the ascent through the atmosphere.

The rocket has a three-axis attitude control stabilisation. It is achieved by autonomous control systems in each stage. The inertial navigation and guidance system in the equipment bay guides the vehicle from the lift-off to injection into orbit. The digital autopilot and closed loop guidance system on board ensure the required attitude change and guides the injection of the satellite into the specified orbit.

GSLV has hundreds of subsystems which are designed, manufactured, tested and qualified before integration for launch. About 150 industries, both public and private, are involved in the supply of materials. However, not all systems can be tested on the ground. Quite a few can be tested and evaluated only in space.

15. A Failure

A Geosynchronous Satellite Launch Vehicle with INSAT-4C on board, launched from Satish Dhawan Space Centre, Sriharikota on July 10, 2006 failed.

A Failure Analysis Committee found out that the propellant regulator in one of the strapon motors had malfunctioned leading to the abrupt stoppage of the motor. With one strapon not working, the other three could not cope with the load. The engine failed at 0.2 second after liftoff and 5 seconds after ignition.

In order to appreciate the failure, it would be useful to have an overview of the mechanism relating to the motor. The first stage of GSLV comprises a solid propellant motor and four liquid propellant strapon motors. The core stage is 20.3m long and 2.1m in diameter. Each of them is loaded with 40 tonnes of hypergolic propellants (UDMH and N2O4) that burn on contact. The strapons as well as the second stage have turbopump-fed engines for imparting the thrust. The strapon motors burn for about 160 seconds and the second stage, for 150 seconds, because of the larger propellant carried by the strapons. On the launch pad, the four liquid propellant motors are ignited first. The solid core stage is ignited 4.6 seconds later after the onboard computer confirms that each of the four strapons has given the rated thrust.

In a turbopump-driven system, a small quantity of each propellant is fed to a gas generator through propellant outlet lines controlled by a regulator. The propellants are burned in a gas generator inside the rocket as an extremely fuel-rich mixture. The output exhaust gas is used to drive a turbine, which in turn drives the oxidizer and fuel pumps through a gear box. The turbine- driven rotary pump increases the propellant pressure to well above the gas generator chamber pressure and delivers the propellant and fuel to the engine injector en route to the thrust chamber at the bottom of the rocket (Fig 6.3).

In the failed GSLV mission, the failure of the propellant regulator led to a larger than normal flow of the propellant. The extra flow created a higher operating pressure in the gas generator. This in turn reduced the inflow of water into the gas generator and triggered a build-up of very high temperature (1823K instead of 900K). The generator broke down in a structural failure. As a consequence, the turbo pump, which gets the input from the gas generator,

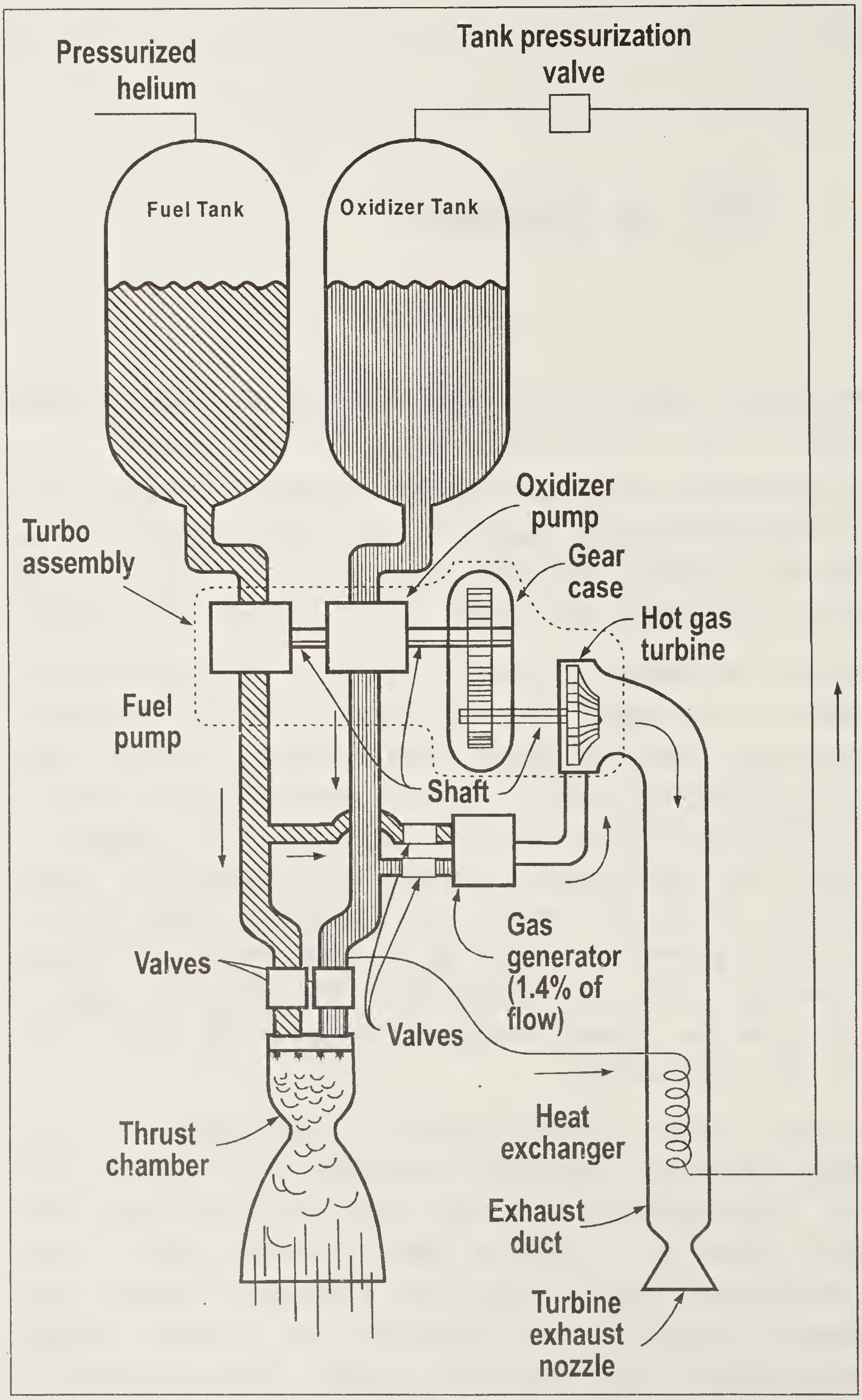


Fig 6.3 : A typical turbo-pump system in a liquid rocket engine. A regulator controls the flow of propellant to a gas generator that drives a turbine to run the oxygen and fuel pumps. Such a regulator failed in the GSLV launch in 2006.

abruptly stopped. With no propellant supply from the turbine pump, the engine failed to provide the thrust.

The regulator, supplied by a private manufacturer, had worked in many previous engines. It can be fully tested only in space in real missions. The malfunction in the regulator must have occurred after the computer had cleared the launch. It could not have been detected in advance.

The Failure Analysis Committee pointed out that the basic design of the GSLV was robust, and suggested that the automatic launch sequence be strengthened.

Similar Failures

Propellant flow problems have been the cause of failure of many advanced rockets. In 1998 the Japanese H -II rocket's second stage failed as the turbine propellant was unable to flow into the engine through a valve. It was later found that a leak detector was by mistake continued to hang on to the intake valve.

In 2004, Boeing's first Delta Heavy rocket suffered a premature engine shutdown. It was later thought that the flow of super cold liquid oxygen in three core boosters might have created bubbles, which tricked the sensors into concluding that the motors had run out of fuel, leading to a shutdown.

In March 2006, the maiden mission of Falcon rocket of SpaceX, an innovative private venture, failed, 25 seconds after lift-off. A fire caused by a fuel leak was thought to be the reason. A review board has since traced the failure to a busted nut and not to a loose pipe fitting— designed to hold the fuel pump's inlet pressure transducer. The two- stage rocket is designed to work on liquid oxygen and kerosene. The first stage was to be recovered by parachute for reuse. The leak of kerosene caused the main engine to catch fire.

The $5 a piece nut had corroded in the tropical heat and humidity of the launch site on the Kwajalein atoll in the Pacific Ocean. It is now proposed to replace the nut with a cheaper (!) stainless steel nut and increase the reliability. It is interesting to note that the Falcon engine is not turbo-fed but pressure-fed. Falcon is claimed to have the highest performing gas generator cycle with kerosene ever built. It seeks to avoid the weight of the turbo engines and reduce the weight of the propellant tanks. The new idea is to use low- pressure rocket engines that work with hypergolic fuels that remain liquid under their own vapour pressure.

Falcon has another interesting feature. It will hold the launch before release after the first stage engine starts, to make sure that all propulsion systems are normal. It has an automatic safe shutdown system and provision for unloading the propellants. The rocket has triple redundant flight computers and inertial guidance. The engine architecture is an improved version of the Saturn V rocket used for the Apollo programmes. The philosophy is that even if some small engines in a rocket fail, the mission should go on.

In both GSLV and Falcon missions the damage was caused by relatively minor components though the systems were perfect.

16. The Cryogenic Challenge

Cryogenic propellants such as liquid hydrogen and liquid oxygen (which can only exist at ultra cold temperatures) give much higher specific impulses, from 445 to 461 seconds, than that given by solid or earth-storable liquid propellants.

A rocket engine, which uses cryogenic propellants, is called a cryogenic engine and the rocket propulsion using such an engine, cryogenic propulsion. Cryogenic propulsion would be needed to lift heavier payloads. A cryogenic rocket engine can be started and shut off at will—a requirement for use in space operations. Moreover, it is free of pollution, as only steam is the resultant product. There is therefore a growing demand today for the use of cryogenic propellants. GSLV third stage, for example, uses cryogenic propellants.

Cryogenic propellants have unique properties. Oxygen and hydrogen become liquefied at minus 183 deg, and minus 253 deg, respectively. Liquid oxygen (LOX) boils at 90K at atmospheric pressure. It has a specific gravity of 1.14. It is widely used as an oxidizer. Along with liquid hydrogen, it gives very high specific impulses. LOX is nontoxic and noncorrosive. This oxidizer has been used in Space Shuttle, the Centaur upper stage, Ariane and GSLV.

Of all known fuels, liquid hydrogen (LH2) is the lightest and the coldest, having a specific gravity of 0.07 and a boiling point of about 20K. The low density demands huge tanks and the low temperature needs special insulation. All common liquids and gases solidify in liquid hydrogen. Hence care is taken to purge all lines with gaseous helium before introducing the propellant. If LH2 were mixed with air or solid oxygen, it would explode.

The thermal energy from cryogenic combustion is in the form of hot gases, the temperatures ranging from 2500 to 3500 ° C, which have high pressure (up to 200 bar). Hot gases expand and provide the thrust. The cumbustion chamber needs adequate cooling. The chamber is therefore made in two shells with passages in between the inner and outer shells for one of the propellants to flow through before entering the combustion chamber—a process known as regenerative cooling. Another technique is called ablative cooling, where an insulating material is bonded to the inner surface of the chamber upto the throat region, which is burnt out to protect the inner wall of the chamber

Propellants in the main tanks are taken to the rocket's thrust chamber at a specified rate and pressure. Feed systems can be either pressure-fed or pump-fed. In the pressure-fed system, a high-pressure gas displaces the propellant from the tank. In the other system, the propellants are sucked by pumps and fed to the chamber. The pumps are driven by turbines, which derive their power from the expansion of hot gases obtained from a gas generator. Since the propellants have very low density, they have to be pumped at a very high speed. The turbo pump therefore rotates at about 40,000 rpm. As a turbo pump has both hot and cold gases, the material selected for making the pump should be suitable for the purpose. The material selected should have a high strength-to-weight ratio, easy to fabricate, better mechanical and physical properties and preferable available at reasonable cost. Accordingly, special aluminium, copper, nickel and titanium alloys as well as special stainless steel are used. Special seals are needed, as ordinary seals will collapse at the cryogenic temperatures. Instrumentation and safety systems are also critical areas.

It is not enough to make only a cryo engine. It has to work in a stage with major subsystems like propellant tanks, which should be kept under pressure (300 bar), fill and drain system, command system with valves, a gimbal system, which will change the axis of thrust as required, a pogo system, which will counter the vibration of the propellant induced by the structure itself and propellant separation system. Moreover, the challenges in cryogenic propulsion include ensuring a correct mixture ratio of the propellants.

India is developing the cryogenic engine and the stage to be used after the Russian supply of these rocket parts is ended. To start with, the indigenous engine will have the same specifications as of the Russian engine. The stage containing the engine is 2.8m in diameter and 9.1m long and has a propellant loading of 12.5t of cryogenic fuel that would give 7.5t of thrust. Test facilities were set up in Mahendragiri in Tamil Nadu to evaluate the engine and the stage. The engine has been tested and the stage is under evaluation.

The cryo engine in a GSLV has to function for 720 seconds non-stop. The indigenous engine successfully worked for 1000 seconds. Cumulatively, the ground tests have shown that it has worked for 6250 seconds. The engine is designed to provide a thrust of 7.1t and the two steering engines that are attached to it should give a thrust of 0.2t each.The latter too uses cryogenic propellants. In 2007, the cryo stage was tested for its full flight duration of 720 seconds proving the capability of an indigenous upper stage and the engine of a GSLV.

GSLV Mark III

ISRO has set its targets higher in view of the growing demands for carrying heavier satellites into the geosynchronous transfer orbit (GTO). The present GSLV

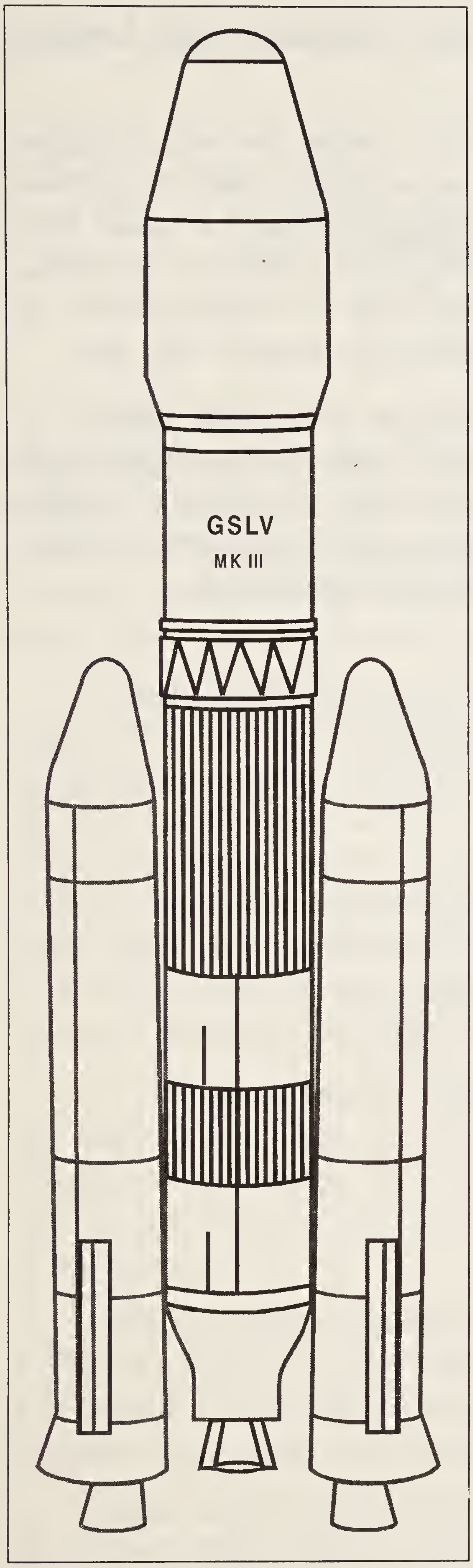


Fig 6.4 : GSLV - MK III.

can place 2.3 tonnes or 2.4 tonnes in GTO. ISRO plans to increase it to 4 tonnes and accordingly it is designing a more powerful rocket called GSLV Mark III (Fig 6.4). It is a three-stage vehicle with a different configuration. It will have a bigger cryo stage, with a loading of 25 tonnes and a thrust of 20 tonnes. The rocket will have a 110 tonne core liquid propellant stage. The core stage will have two Vikas engines. The propellants are earth-storable UDMH and N2No4. The core liquid stage will be supported by two solid propellant strapons, each with 200 tonne propellant, unlike the present design of a solid core stage with four liquid strapons. It will have a lift-off weight of 629 tonnes and will be over 42m tall with a payload volume of 100 cu m. The development of the new rocket is expected to take six years.

Though cryogenic engines are now preferred for upper stages, the trend is to use them even in the lower stages along with augmentation by solid and liquid stages. For example, Ariane and the Space Shuttle use them in lower stages. Future GSLVs would have to consider high thrust engines of 100t to 200t capacity including cryogenic propulsion.

Semicryogenic Rockets

ISRO is also studying an option to make what is known as semicryogenic rockets. It envisages the use of refined kerosene, a shade better than aviation fuel. Kerosene is mixed with liquid oxygen to provide a thrust of 200t, adequate to place 10t in an Earth orbit of 300km. It could serve as a launch platform for other probes such as interplanetary missions. No doubt, the efficiency of the semicryogenic engine is less than a fully cryogenic engine but it is certainly more than that of a conventional liquid engine with earth-storable propellants. The Liquid Propulsion Systems Centre of ISRO in Thiruvananthapuram, which is developing and fabricating the liquid engines and stages, is developing

a proving engine of 10t capacity to try out the new combination with kerosene and liquid oxygen.

Major infrastructure facilities are being set up to realise the new cryogenic rockets. They include a cryogenic test stand and an integrated plant to produce liquid propellants including liquid hydrogen, some 150t a year. LH2 is made from gaseous hydrogen by successive compression, cooling and expansion processes. When mixed with air, it would explode over a wide range of mixture ratios. As a precaution, hydrogen leakage is intentionally ignited and burned with air.

Meeting the cryogenic challenge has the benefit of nationwide spin-off, as do the other programmes of ISRO. Indian industry will have a unique opportunity to contribute to the programme, thereby enhancing its own standards of quality. The programme would need the fabrication of Vikas engines, cryogenic engines, liquid stage propellants and related components and instrumentation.

17. Into the Re-entry Club

None thought of re-entry when the Space Age began but soon when Yuri Gagarin returned to earth, people realised that the vehicle should have stood the heat of re-entry into the Earth's atmosphere. Missiles too needed to reenter the atmosphere to strike at targets. Wind tunnel experiments showed that needle-like missiles would simply burn up in the heat of re-entry. An elaborate search for new alloys that would stand the heat began.

When the shape of the re-entry vehicle in manned missions was under study, Julian Allen of Ames Aeronautical Labs (USA) came up with a brilliant idea. He proposed what he called the blunt body design. The blunt nose of the capsule, he said, would form a thick shock wave ahead of the missile or capsule and deflect the heat. That was in 1952. Soon, General Electric and other companies realised the design. America's Mercury, Gemini and Apollo capsules had blunt body shape and worked well to get the astronauts safely back. Even today there is a strong case for the capsule recovery; the laws of aerodynamics and inertia favour a five-ton bell-shaped capsule over a 100-ton winged shuttle.

A returning capsule should enter the atmosphere at the correct angle. If the angle is too steep, it would burn up and if it is too shallow, it would skip and fly off into space. The correct angle is the result of the reorientation of the vehicle just before re-entry, its weight and speed. Here control and guidance play a significant role.

The successful splashdown of ISRO's Space Capsule Recovery Experiment-1 (SRE-1) from its 12-day orbit into the Bay of Bengal in 2007 as planned marks a milestone on the road to reusable rockets, recovery of microgravity experimental payloads from space and possible manned space missions.

India has joined the so-called re-entry club that has just three members viz. the United States, Russia and China, who have mastered the technology of re-entry of their space capsules into the Earth's atmosphere from orbit.

India can now consolidate its position among the world's leading space powers in international cooperation in space transportation, exploration and scientific projects.

From a circular orbit the SRE was put into an elliptical orbit of 485km perigee and 637 km apogee. The onboard rockets were fired when the capsule was over the Pacific Ocean and 37 minutes after the deboost started, it entered the atmosphere at a height of 100 km at the 8km a second (29,000 km/hour). The capsule was protected from the heat (upto 1400 degrees C) by indigenous carbon -based ablative material and silica tiles on the surface. It may be recalled that the failure of a few tiles on the shuttle led to the Challenger disaster.

At 5 km into the atmosphere, aerodynamic braking reduced the speed of the capsule to 363 km/hr and at a height of 2km, the main parachute opened and the SRE splashed down in the Bay of Bengal at 9.46 A.M. IST, some 45 minutes after the deboost start. Once it hit the water, it triggered the beacon and a dye for easy location by a helicopter from a Coast Guard ship. As planned, it was recovered from the sea at 140 km from SHAR with the help of divers and brought to Ennore in Tamil Nadu by the coast guard vessel, ‘Sarang’.

The ISRO Satellite Centre and the Vikram Sarabhai Space Centre, Thiruvananthapuram played a lead role in building the recoverable satellite. The ISRO Telemetry, Tracking and Command Network, Bangalore tracked the satellite along with a worldwide network of stations. The recovery was done by the Satish Dhawan Space Centre, Sriharikota.

The mission has proved that ISRO is capable of evolving reusable launch vehicles to replace eventually the current once-only rockets and reduce the cost of access to space.

18. A Record of Seven Seconds

The first Indian sounding rocket had a diameter of only 75 millimetres and weighed just 10 kg. When it was launched in 1967, it attained an altitude of 4.2km. After nearly four decades, VSSC has taken another first small step towards a more ambitious goal of developing a modern reusable launcher. Towards that end, a ground test in 2006 demonstrated a stable combustion of fuel with the inlet of oxygen at six times the speed of sound (supersonic), a typical feature in what is known as a scramjet. The combustion lasted only seven seconds, but like the first rocket, it was a breakthrough in the efforts to design, develop and realise a scramjet.

Known as supersonic combustion ramjet, it calls for mixing of very high speed air (at 1.5 km/sec) with fuel and achieving a stable ignition and efficient combustion.

The combustion was part of a reusable launch vehicle (RLV) technology development project of ISRO. A scramjet engine is needed to develop a reusable rocket, reducing the cost of a launch. It is estimated that the launching a kilogram into space costs $ 12,000 – 20,000. The aim now is to reduce the cost to $500 - 1000. This would mean a totally different technology and configuration of rockets. One such approach is to design a reusable launch vehicle and use it in the rocket's upper stage in place of the current once-only rockets. This would be facilitated, if the weight of the rocket can be reduced, while increasing its efficiency. An important way of reducing the weight is to reduce the quantity of fuel taken by a rocket.

Today almost 90 percent of a spacecraft's launch vehicle is fuel. It is now planned to use the oxygen in the air instead of taking it in fuel tanks. This is known as the air-breathing propulsion, used in today's jet planes. However, in a jet aircraft, the air is sucked in but it is compressed by rotating blades before combustion and expansion to provide the thrust. A turbojet can go up to Mach-3 only. But if the air were taken in at supersonic speeds of more than Mach-4 (four times the speed of sound, (which is 750km per second), there would be no need for rotating blades. The airflow would be compressed by the forward velocity of the rocket and its aerodynamic design, as it enters the engine where

hydrogen fuel is added for combustion. The expanding hot gases from combustion accelerate the exhaust air and create thrust (Fig 6.5).

The efficiency of a scramjet is rated as 2500 to 3000 seconds, as against about 400 seconds given by cryogenic engines.

The engine, called scramjet (supersonic combustion ramjet), would be thrice as efficient as the conventional liquid or solid rocket. At such high speeds, the properties of the air change resulting in a rapid increase in temperature to over 1000 deg C. A contributory factor for the tremendous heat is the horizontal trajectory of the rocket in order to get the maximum oxygen, which begins to thin out above its densest range of 10 to 20 km.

ISRO aims to achieving the orbit in two stages. The other aim, single stage-to-orbit is not being attempted right now. The RLV will have a booster, which uses semi-cryogenic fuel, kerosene and liquid oxygen. The fuel would be unlike the fully cryogenic fuel now being used for the last stage of a GSLV.

The semi-cryogenic fuel is nontoxic and easy to handle. The upper stage of a RLV will be a reusable demonstrator vehicle and will be released at a given altitude. At the end of the mission, reaction control systems will help deorbit the stage, which will be brought down by parachutes in the atmosphere. Initially it is planned to splash down in the Bay of Bengal at some identified location away from Sriharikota (SHAR). Subsequently, a RLV will be fitted with landing gears and will land like an aircraft at SHAR. Air-breathing engines in RLV will be introduced at a later stage after understanding various technologies associated with RLV.

The project will give ISRO experience in recovering and using again the stages sent into space. Hypersonic aerodynamics, thermal protection systems and autonomous control and guidance are crucial for the success of reusable vehicles. It is essential that these complex technologies are mastered.

'Intelligent' sensors would help in the autonomous functioning of the rocket's guidance system. ISRO has rich experience in the design of control systems. In the ASLV for example, the engineers introduced what is known as the closed loop guidance system. It is a real time decision - making system based on a comparison of the actual motor pressure with the given values and actuate the autopilot to take corrective action, if need be.

ISRO has continued R&D on air-breathing propulsion and has carried out a number of supersonic combustion tests on ground successfully. Based on these tests, it is planned to flight test air-breathing engine for demonstrating the scramjet propulsion using a two-stage RH-560 sounding rocket.

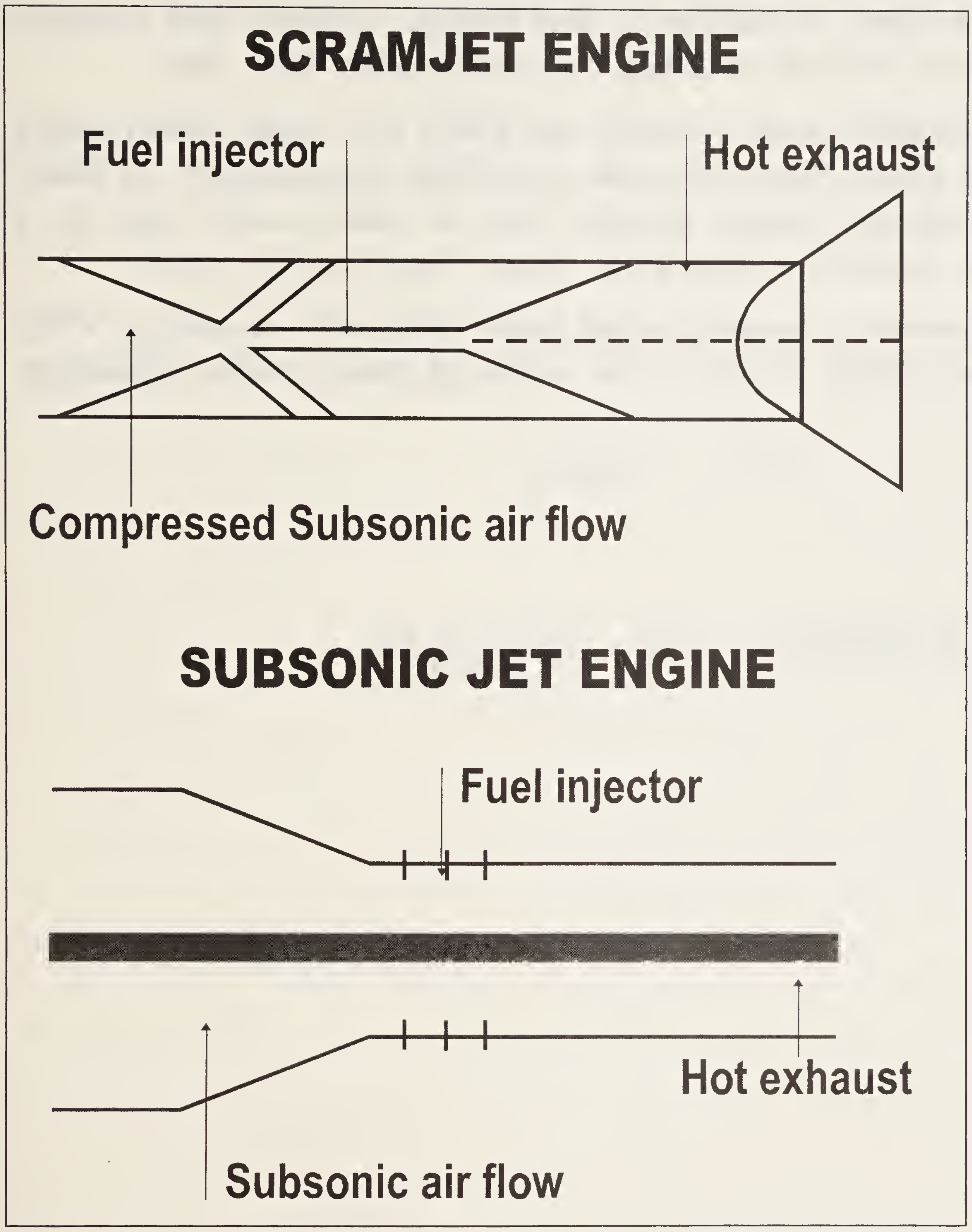


Fig 6.5 : An air- breathing engine draws oxygen from the air and can be reused. Compressed air flow at subsonic speed is mixed with fuel in a jet engine, while in a scramjet engine, the compressed air flow will be drawn in at supersonic speed.

A Reusable Rocket

New developments in materials production and electronics have greatly boosted the effort to reduce the weight of the reusable rocket. Thermal protection is crucial, as the rocket will encounter severe thermal forces (touching 2800Kelvin) and aerodynamics during its ascent and descent phases. During reentry into the Earth's atmosphere, the rocket would just burn up unless protected. Some advanced concepts are under study for thermal protection including composites of carbon and silicon carbide, c-foam, noted for its ultra-light weight but high temperature, gamma titanium aluminides that retain the properties at high temperature, materials that can change their contours according to thermal loads, and shape memory alloys (e.g. Nitinol), which return to their original shape after suffering deformation. Other materials include graphite epoxy composites and aluminium-lithium alloy for fuel tanks. Advances in electronics have dramatically reduced the size and weight of the components. Nanotechnology-based materials, light-weight but super strong would also emerge soon.

Another development has added a new dimension to testing the structures in conditions similar to space. In addition to wind tunnels, computer fluid dynamics has emerged as a new way of obtaining the aerodynamic flow data.

Though some countries such as Russia and China have done ground testing of scramjets, only the United States has made an in-flight demonstration. In March 2004, an X-43A, a research vehicle launched from a rocket carried aloft by a conventional airplane, attained a hypersonic (more than Mach-5) speed.

The first step towards a reusable rocket lasted only seven seconds at VSSC but it marked a new exciting journey in the annals of India's rocket technology.

PART - VII

INSATs IN ORBIT

19. Studies and Experiments

In the late sixties, several studies were carried out to examine the feasibility of domestic geostationary satellite system. In March 1970 Dr. Sarabhai presented a paper providing the broad details of the Indian National Satellite System (INSAT). The paper set out the basic approach of procuring the first set of satellites from abroad and of building the subsequent series in India. However, there was still debate on the relative merits of terrestrial versus space system. A national seminar in 1972 emphasised that satellite and terrestrial media should be considered as complementary and not competing systems. A hybrid system combining the best of both systems would be cost-effective, flexible and efficient.

Further studies were supported by several experiments such as SITE. Different services (such as point-to-multipoint links, transportable earth stations) were found feasible. The Government set up a high-level committee in 1975 to work out the scope, timing and implementation strategy of satellite communication. In order to provide telecommunications, television and weather data, a three-in-one satellite concept was pursued. A total of eight different configurations were studied. Though a three-in-one satellite was complex, it was found cost-effective. Agriculture demanded weather information; telecommunication promised good revenue; and the results of SITE favoured satellite-based television. The crowded geostationary orbit further expedited decisions on the ground. The place in the orbit had to be negotiated with Indonesia, Russia and INTELSAT at international conferences convened by ITU in 1979, 1985 and 1988. As a result, two orbital slots viz. 74°E and 93.5°E were coordinated and registered.

The INSAT programme emerged as a joint venture of four Ministries of the Government of India dealing with Space, Telecommunciations, Information and Broadcasting and Science and Technology, respectively. The first green signal to implement INSAT was given in July 1977. A contract to build two INSAT-1 spacecraft was awarded to Ford Aerospace Corporation of USA (now Space Systems/Loral) in 1978.

APPLE : A Unique Experiment

Meanwhile, ISRO decided to develop an indigenous satellite with the latest features. An opportunity came from the Ariane rocket management. An ISRO team made the satellite in a record time of three years.

On June 19, 1981, Kourou in French Guiana was the center of eager expectations. The third test flight of the European Space Agency's (ESA) Ariane rocket was about to begin. The countdown was interrupted by minor snags in the radar. The launch was held up for about 73 minutes. The blast-off came at 12 hours, 32 minutes and 16 seconds Greenwich Mean Time (GMT). The European and Indian space experts and technicians were elated. For the Europeans, it was a relief as only 13 months earlier, they were beset by the failure of a similar rocket. For India, Ariane launched its first experimental, geostationary, communication satellite called APPLE (short for Ariane Passenger Payload Experiment), the result of three years of hard work by 1,500 Indian engineers and scientists (Fig 7.1).

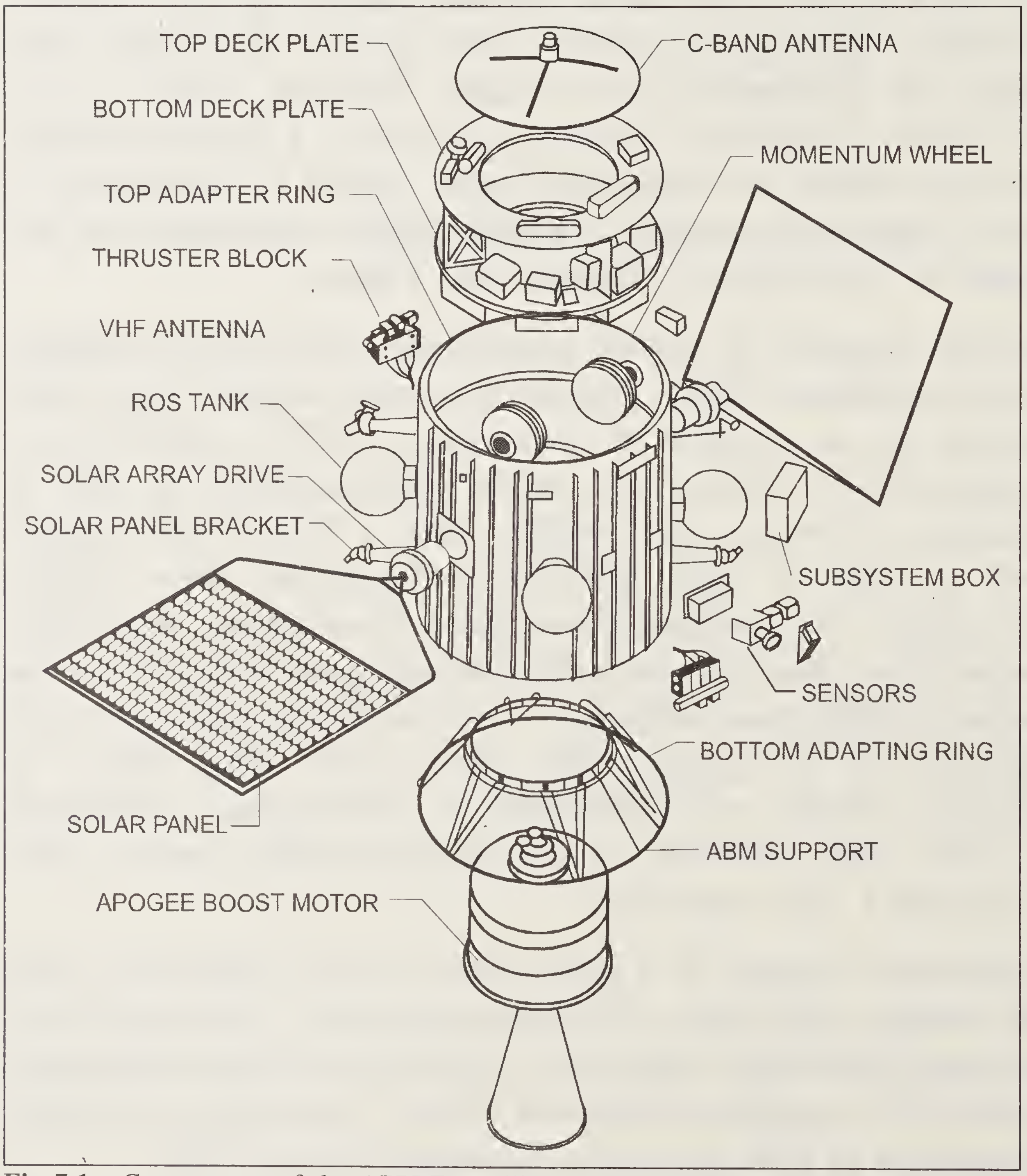


Fig 7.1 : Components of the APPLE satellite, the first experimental geosynchronous satellite, made in India.

Within 17 minutes, Ariane injected an European weather satellite, Meteosat, APPLE and a technological capsule into geostationary transfer orbit (GTO). APPLE was sandwiched between two other satellites. Thirty minutes after the liftoff, tracking stations in Sriharikota, Ahmedabad, Bangalore, Fiji and Kourou started getting signals from APPLE. Made at the ISRO Satellite Centre at Bangalore, the satellite was found to be in good shape after the launch. The first orbit had a perigee of 201 km and apogee of 36,206 km. Its inclination was 10.5 degrees and the orbital time was estimated at 10 hours 39.8 minutes. This was the transfer orbit. At a suitable chosen

moment, the spacecraft was to be transferred to the higher, geostationary orbit over the equator and positioned over 102° East longitude.

Transfer to Synchronous Orbit

The transfer was to be made by the onboard apogee boost motor (ABM) which was an improvised version of the fourth stage of SLV-3. It was decided to fire the ABM on the sixth transfer orbit. This was a big challenge for the Indians as it was their first attempt. The ABM with its solid propellants cannot be switched on and off, once ignited. (A liquid apogee motor was developed later). There was only one chance to kick the spacecraft from the elliptical to the planned, circular geostationary orbit. It had to be fired on radio command when the spacecraft was at its farthest point from the Earth in its transfer orbit. The experts were confident that it would work. They had tested several motors in ground conditions similar to those in space. Made of fibre-glass casing, ABM, which weighed 320 kg, had 272 kg of solid propellants, and could burn for 33 seconds, producing a thrust of 2.2 tonnes. The ideal orbit for firing the ABM was chosen with the help of computers at Sriharikota. It was successfully fired on June 22.

ABM's capacity for velocity increment was originally estimated at 1530 metres a second to a mass of 630 kg in a transfer orbit of 20 km by 35,800 km so as to reach a near-24 hour equatorial orbit of 35,800 km. APPLE weighed 673 kg at lift-off and so the velocity increment after ABM firing was limited to 1440 m/sec. This resulted in a near 22 hour equatorial orbit with an apogee of about 35,80 km and a perigee of 31,000 km. The incremental velocity still required to take it to a 24-hour equatorial orbit was to be provided by the 16 hydrazine thrusters on board APPLE. At lift-off, the hydrazine loaded on board was 42.5 kg as allowed by the launcher authorities. A major part of it was to be used for imparting the incremental velocity that was still needed. It was time for the next major step. The spacecraft which was spinning at 60 rpm was despun to 0.5 rpm in preparation for the deployment of the solar panels. Power was to be derived from two solar panels that would track the Sun in a deployed mode. The two arrays were meant to provide 210W at the end of two years. A nickel-cadmium storage battery of 240W capacity met the power needs during the initial ascent of the satellite and during the orbital eclipse period.

Moments of Joy and Agony

The mission seemed normal, but one of the two solar panels failed to deploy. Undaunted, the scientists again spun up and reversed the spin direction of APPLE but still the panel did not open. The moment of joy that marked the firing of ABM was followed by hours of agony. All other systems were working

well. The telemetry data were reaching the control center. The telecommands were reaching the satellite. The tracking was excellent. The transponder payload onboard, designed and made by the Space Applications Centre (SAC), Ahmedabad, worked without a flaw and was found fully compatible with the ground equipment that was earlier set up for experiments with a Franco-German satellite, Symphonie. The 900 mm graphite fibre reflector, made at the VSSC relayed the signals clearly.

As electrical power from one panel was found adequate for continuing the mission and as thermal control was possible by proper management of the heat load of the spacecraft, it was decided to go ahead for the three-axis attitude acquisition. The first step was to acquire the Sun. It was complicated as the Sun sensors were partly blocked by the undeployed north solar panel. Still, an attempt was made to set things right but without success. It was then decided to use another Sun sensor with a limited field of view on the east face of the spacecraft under a modified procedure. The Sun was acquired but Earth acquisition could not be completed in time. The scientists held emergency meetings. After 32 hours of continuous deliberations and scores of telecommands, they decided to continue the rest of the operations, though half of the power capacity was adequate for all the experiments.

On June 24, the Earth was acquired as planned. Then the control was transferred from the hydrazine thrusters to a momentum wheel, so that the spacecraft had three-axis stability and stayed pointed towards Nagpur in India which was the centre of its beam. The attitude and orbit control system consisted of momentum wheel assemblies that provided pitch control so that the pitch axis (North-South direction) was steady. Despite the asymmetry caused by the non-deployment of a solar panel, the axis was steady. The system also had hydrazine reaction control with redundant devices to guide and control the spacecraft in its transfer orbit, and to control roll or yaw deviations and help maintain three-axis stability. A magnetic torquer was provided as an additional device to control the roll axis. Sensors to spot the Earth and the Sun were provided. Suitable electronics for achieving, spin, despin, attitude control and dumping excess momentum were housed in the system. A passive system for thermal control was used, consisting of multiplayer insulation blankets, optical solar reflectors, thermal paints, thermally treated surfaces and heaters.

Halting the Drift

Having acquired the Sun and the Earth, the scientists resumed their efforts to solve the problem of incremental velocity required to get to the precise 24-hour geosynchronous orbit. The operations had to be done quickly as from 24 June the spacecraft would move away and it would take eight days for it to

return to the same spot. The initial height reached was very much lower and as a result, the spacecraft moved faster than the Earth. The satellite's orbit had to be raised and its eastward drift arrested. The faster depletion of hydrazine meant a shorter life span of the satellite, which was designed for an active life of two years. The useful life was shortened not because of the nondeployment of a solar panel as was some times imagined but because of the unexpected use of fuel for orbit raising.

The hydrazine thrusters were fired for 44 minutes on June 24 and the eastward drift was progressively reduced from 35° a day to 7.7°. Still the spacecraft had moved over to 120° E longitude over Indonesia. The satellite was moving 33 minutes faster than the Earth's rotational speed. Subsequent firings arrested the eastward drift. Mission control adjusted the perigee and the apogee of the egg-shaped orbit in such a way that they moved APPLE to a higher orbit to give it a westward drift as it assigned position was 102° E longitude. Its orbital period then became 2.4 minutes slower than the Earth's 24 hour period. The drift westward was increased after June 27.

The Odyssey Ends

On July 16, 1981, APPLE reached its assigned position, after a final 85-second firing of hydrazine thrusters. In all, the thrusters were fired eight times since June 24. In its 28-day space Odyssey, the satellite responded to all commands except the one relating to the solar panel. The duration of the geosynchronous orbit reached was 23 hours, 56 minutes and 41 seconds. It was a breakthrough in satellite command and control technology for India.

When the 90 cm antenna on board pointed towards Nagpur and the test signal was received well, India joined the select group of countries (U.S.A., Russia, Canada, Germany and France) that had designed and built three-axis synchronous communication satellites. The on-orbit checkout of the communication payload was done in about three weeks. The TV signals were found excellent. When all the tests were completed, the utilisation phase began from August 13, 1981. The Prime Minister of India formally inaugurated the satellite programme at a teleconference held between New Delhi and Ahmedabad relayed in real time by the TV stations all over the country.

A Greater Challenge

If positioning APPLE at the planned slot was a major achievement in the light of what happened after ABM firing, the in-orbit management of the spacecraft proved a greater challenge. The deviations caused in the roll axis of the satellite by the non-deployed solar panel were within the capacity of the attitude control

system, though fuel consumption was marginally increased by it. However, the undeployed solar panel covered the solar radiators on the north side, thereby losing almost half the radiating area. This resulted in the entire spacecraft getting hotter than was expected. Thermal load management became crucial to ensure the survival of the critical subsystems. In October 1981, the spacecraft went through its first in-orbit eclipse smoothly, when it was under the Earth's shadow for a while. As the Sun came increasingly on the south face of the satellite, the rise in temperature was posing serious problems for some of the onboard systems like Earth sensors. The APPLE mission took a bold, innovative decision to rotate the satellite slowly at the rate of one revolution per hour for 3 to 4 hours a day. This is known as pitch rotation. They did this around local midnight. They had to command the spacecraft to delink it from the Earth lock for this purpose. During the orbital eclipse, the communication payload was not operated as a precaution. Meanwhile, user interest built up considerably. But, in view of the heat problem, the operation was restricted to about 14 hours a day. Its orbit was determined regularly. A careful watch was kept on the satellite's various parameters such as its temperature. By December 1982, over 80,000 commands had gone to APPLE. It was noteworthy that only one command was found erroneous, as a ground console was defective. Regular heat budget management involving dumping of excess heat, as the radiators in the north face were blocked, had kept the engineers busy. The satellite became a virtual "orbital laboratory" until it was abandoned on September 19, 1983 after 27 months in space.

Indigenous Momentum Wheel

An important development took place on July 19, 1982, just after a year of its launch. The imported momentum wheel was switched off and its indigenous counterpart took over. About 1000 commands went out for this purpose. In 40 minutes, the wheel rose to its nominal speed of 3500 revolutions a minute. From then onwards, attitude control of APPLE about its pitch axis was done by the indigenous device within the limits of plus or minus 0.1°.

The ISRO team opted for major challenges right from the beginning of the project. When ESA offered two proposals to fly free of charge (either a 150-kg autonomous dual spin communication satellite or a communication payload on board an European satellite), ISRO went in for an independent and more ambitious three-axis body stabilized communications satellite – one of the latest concepts. Despite the tight time schedule of about 36 months, ISRO decided to devise not only a novel system but to introduce several indigenous technologies such as the apogee boost motor, the Earth sensor, the momentum wheel, communication payload, driven/deployable solar panels, and systems for tracking, besides telemetry and telecommand. These devices would be of great importance in later missions.

Permanent Assets

A notable feature of the Mission was the creation of permanent assets. They include the thermovac chamber, high altitude test facility for ABM later developed as liquid apogee motors, firing, augmentation of the tracking network and a host of other related activities. An unexpected benefit was noticed when problems that cropped up on board the spacecraft were successfully solved by persons normally in the fourth or fifth level of decision-making. Extensive simulation studies were conducted. Quick consultations and combined wisdom covering many disciplines helped to face the task successfully. No effort was spared in perfecting the satellite. Five models – structural, thermal, engineering, prototype and flight – were made and tested under conditions that were more severe than were actually encountered.

Several Experiments

Even with limited power on board, the satellite was useful to conduct several experiments. They related to areas such as digital communication technology, broadcasts and telecasts, data communication and computer interworking. Several advanced concepts were tried. One of them, for example, is known as time division multiple access, under which different Earth stations can time-share a 'speech highway' to a satellite. Use of emergency communication terminals through the satellite in times of cyclones was also tried. The then P&T Department, Doordarshan (TV), Akashavani (AIR), the Indian Institutes of Technology, Defence, Electronics and Computer organisations were also involved. *The Hindu* conducted facsimile transmission of its pages from Madras to Bangalore. Thanks to APPLE, several national events such as the Republic Day could be telecast and seen from various parts of the country at the same time. Efforts were also made to speed up wagon movements on the railways and expedite interbank transactions. A five-hour advanced course on robotics (on the use of robots) was beamed through APPLE simultaneously to scientists in many cities. The aging satellite was drifting slightly in orbit leading to some trouble in picture transmission, but the audio was good.

A nationwide effort had made APPLE a reality. The project management, overall design and development, fabrication of the basic spacecraft, integration and testing for ensuring quality were carried out by the ISRO Satellite Centre, Bangalore. VSSC developed the ABM, the momentum wheel, the C-Band reflector and the solar panel deployment mechanism. SAC designed and made the communication payload, while SHAR provided additional testing facilities and assisted the Mission Control Centre. Several public sector units were also involved. They included Hindustan Aeronautics Ltd., Bharat Electronics, National Aeronautical Laboratory, Defence, and Metallurgical Research Laboratory. The imported components consisted

of reaction control system, the solar array drive assembly, nickel-cadmium batteries, solar panels and scanning Earth sensors and communication devices such as travelling wave tube. Want of adequate infrastructure facilities held back the development of several devices in the country; most of them have since been made indigenously. The technology base and the infrastructure gained through APPLE enabled India to build operational satellites for communications, remote sensing and meteorological observations.

20. The Rise and Fall of INSAT-1A

Even as the experiment of APPLE continued, the first operational satellite, INSAT-1A was launched in 1982 but the mission ended prematurely five months later. Unlike APPLE which was placed in a synchronous transfer orbit straightaway after launch, INSAT was placed in a low Earth orbit by a two-stage Delta 3910 rocket, followed by injection into the transfer orbit by the Payload Assist Module (PAM) of the rocket.

The launch took place on April 10, 1982. There were heavy rains and high winds. The weather cleared for a while and the countdown went ahead. The lift-off was at 1217 IST, just after the launch window opened. By then the launch was twice delayed. Some 40 minutes after lift-off, the Master Control Facility (MCF) at Hassan established contact with INSAT.

PAM was separated by command from MCF, INSAT was put into a transfer orbit. It was highly elliptical with a perigee of 185 km and apogee of 35,405 km. The satellite was despun, the Sun was acquired and the solar array was partly deployed. Then came the first major snag. The C-band antenna did not open. It was blocking four out of the 12 thrusters on board.

The Earth was "acquired" by the satellite. The apogee motor was first fired. It lasted 34 minutes and 24 seconds. The satellite was raised to the intermediate orbit, with a perigee of 11,305 km and an apogee of 35,139 km. The orbital period was 14 hours. Later, the spacecraft was eclipsed from the Sun by the Earth. There was no signal from the spacecraft for 12 hours.

Solar Sail Disobeys

MCF acquired the signal and fired the apogee motor for the second time. The thruster fired for about 21 minutes, when the satellite crossed its apogee for the third time. INSAT was nominally put into the synchronous orbit. The solar array was fully deployed, after some hitch. The momentum wheel was spun up. Then came the biggest snag viz., the solar sail and its boom did not open.

As a result, the attitude control system had to compensate the solar torque on the solar array and sail. Fuel consumption went up. The fuel was meant for keeping the satellite steady for seven years. As four thrusters were on one side,

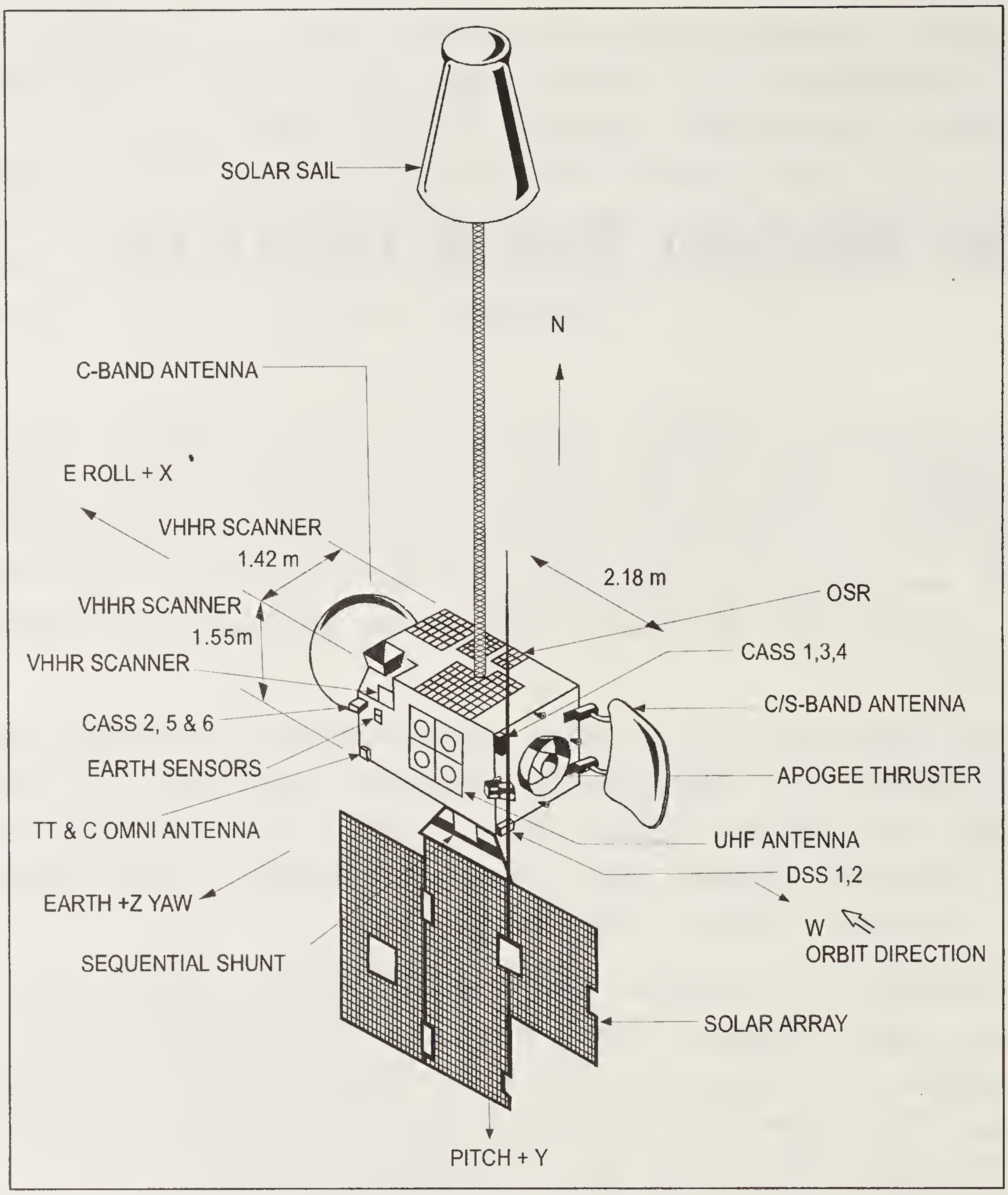


Fig 7.2 : On - Orbit Configuration of INSAT-1 and INSAT-2. INSAT 2 was about 50 per cent heavier and have higher capabilities. Also there was no need for a partial deployment of solar panels.

the mission control had to turn the satellite around to give it the needed thrust in the correct direction.

On-orbit testing of the subsystems was done in the next fortnight (Fig 7.2). Hassan acquired the satellite by the end of April over 74°E longitude. The C-band was deployed and all thrusters became available. The spacecraft was declared operational from May 15. As the fuel consumption was high, the satellite's life was estimated at about two and a half years as against the design life of seven years.

The undeployed solar sail was acting as an effective shield covering three-fourths of the surface preventing the heat from going out. As the heat radiating surfaces were covered, TV operation was affected. Whenever the TV (S-band) L transponders were operated, the heat build-up degraded the batteries. Television broadcast had to be restricted to only 5 to 6 hours a day. However, the other systems such as the communications, meteorological and data transmission payloads continued to work.

The Moon Intervenes

On August 31, 1982 INSAT and a few other synchronous satellites entered an eclipse season. However, the asymmetric spacecraft experienced some error

in its yaw axis directed towards the Earth. INSAT's controls started correcting the error automatically. The Sun was sometimes visible in the Earth sensor (because of the movement of celestial bodies). Such Sun intrusion was predicted by computers but when the Sun interference was prolonged, ground controllers ordered the inhibition of the Earth sensor. The Earth lock was maintained by the other Earth sensor. Shortly afterwards, the satellite did not respond to the commands. Within a few hours, all contacts were lost, Ground controllers struggled to find out the reason. Detailed analysis of data later revealed something totally unexpected. When only one of its Earth sensors was functioning, it caught the full moon, a phenomenon which was totally unpredicted and entirely unexpected. The sensor was automatically inhibited by the lunar glare and as the north scan sensor had also been cut off, the spacecraft lost the Earth lock.

"Losing Earth" is not a nightmare for satellite controllers. They had lost and reacquired it on several occasions, but only when they were able to command the satellite. The standard practice is to switch to the omnidirectional antenna of the satellite. But INSAT controllers could not establish a link with the omnidirectional antenna. Some telemetry data were received but the commands were in the 'blind' mode. It was not known whether the commands were received or obeyed. A safety isolation switch to prevent the flow of propellants was switched on. But the critical commands were not received on board. A wrong pulse resulted in the depletion of hydrazine. The oxidizer also started flowing. In less than an hour, the entire propellants were exhausted. The satellite started drifting and soon disappeared.

Notwithstanding the failure, INSAT-1B was launched in June 1983. It continued service until July 31, 1990 when INSAT-1D went into operation. Following the failure of INSAT-1A, INSAT-1C was chosen as its replacement. But INSAT-1C was delayed until July 1988 because of launch vehicle failures. Shortly after launch, INSAT-1C experienced a short-circuit in one of its power systems and had to be operated with about half its capacity for 16 months, when it lost its Earth lock following a systems failure. ISAT-1D was scheduled for launch in June 1989 to serve the transition period between the INSAT-1 and –2 series. INSAT-1D, could be launched only in June 1990, following an accident on the launch pad which damaged the spacecraft.

The INSAT-1 system was envisaged with two satellites. However, such a system could be achieved only after INSAT-2A was in operation. But by mid-1985 (within two years of launching INSAT-1B) all the targets of utilisation including TV, were achieved. In order to augment the service, some capacity was leased from ARABSAT for three years (October 1989 to September 1992) and from INTERSPUTNIK and INTELSAT for shorter periods.

21. The INSAT-2 Series : An Indigenous Effort

In fact, preliminary studies for defining the second generation of INSAT began in 1979, as the decision to build INSAT-2 spacecraft in India had been taken when the first series was approved. Even as APPLE was shipped to Kourou, the first study on proto-INSAT was made in June 1981 by ISRO. The original strategy was to launch the first INSAT-2 test satellite in 1989 and the second after one year, to be followed by operational satellites. But the launch of INSAT-2 was delayed by about two and a half years. INSAT-2A was launched only in June, 1992 followed by INSAT-2B in July, 1993. The in-orbit performance of the two spacecraft was excellent and hence they were used in an operational mode. Thus, the transition to the second generation occurred by 1992 as envisaged earlier. The configuration of the INSAT-2 series was based on four considerations: one, the need for continuity of service; two, increased capacity for telecommunications and broadcasting; three, improved resolution of the meteorological payload; and four, introduction of new services such as mobile phone and improved facilities for business communications (Fig 7.2).

Accordingly, the INSAT system was oriented to meet the following technical needs :

- a large increase in the telecommunication earth stations to link remote areas.
- introduction of digital networks using VSAT stations to link remote areas.
- introduction of several services in the S-band.
- increase in TV channels in the C-band.
- rapid expansion of regional TV networking.

New Technologies

INSAT-2A and 2-B, launched in July 10, 1992 and July 23, 1993, respectively were totally indigenous. They ushered in a new era in space communications in the country. The satellites have provided continuity of services, increased capacity for telecommunications and broadcasting and better resolution for the meteorological payload.

The payload of INSAT-2 weighed 240 kg as against 130 kg in INSAT-1. The lift-off weight of INSAT-2 was 1900 kg, 700 kg more than INSAT-1.

Several new technologies were developed and introduced successfully: solid-state power amplifiers; integrated receivers for both C-bank and extended C-band, reflectors, antennas working all the way from S-band to extended C-band; momentum wheels, reaction wheels, solar array drive, pyrotechnic cutters, inertial reference unit, bipropellant-based altitude and orbital control systems, liquid apogee motor, hybrid microcircuits, radiation-hardened microprocessors, light-weight solar arrays and deployment mechanism. Most of these technologies were developed for the first time in India. As all the subsystems had to meet very high performance standards and work for at least seven years, sophisticated test facilities were set up. The facilities include a large solar simulation chamber, automated test facilities for payload testing, use of computerised planning and monitoring system and automated testing of communication payloads.

Based on experience, certain unique features were introduced in the INSAT-2 configurations. A different procedure was adopted for the deployment of solar panels. Partial deployment of the solar panels as done in INSAT-1 was avoided to reduce complexity. An alternative scheme was adopted. Accordingly the spacecraft's south face was made to point to the Sun in the transfer orbit with the solar panels folded and stowed on the south panel. The outermost panel alone has the solar panels exposed. In this mode, the Earth is automatically aligned with the Earth sensor in the satellite's north face.

An innovative method was adopted in locating identical satellites, especially because the number of slots in the geostationary orbit is limited. It is therefore necessary to make the fullest use of each available slot.

Some technological problems are, however, involved in collocation. The angular separation of the satellites should be less than 0.05° with a negligible probability of collision. ISRO did several studies on the strategy of collocation.

INSAT-2C and New Services

With the successful operation of INSAT-2A and 2-B and the availability of INSAT-1D, there was ample provision for weather monitoring and data relay. Hence the next satellites in the series, INSAT-2C and 2D were designed without the weather monitoring payload. As a result, the shape of the satellite is different; there are solar panels on either side. Instead of the meteorological payload, some new services are provided.

INSAT-2C, the third in the INSAT-2 series of satellites, designed and built by ISRO, was launched by an Ariane rocket on December 7, 1995 (Fig 7.3).

The components of the INSAT-2C payloads were :

a) Fixed Satellite Services :

- Two 50W, seven 10W and three 4W transponders in C-band.

- Two 10W and four 4W transponders in extended C-band

- Three 20W Ku-band transponders and a Ku-band beacon.

b) Broadcast Satellite Services

One transponder operating in C-band for the uplink and S-band for the downlink for TV and radio broadcasts.

c) Mobile Satellite Services :

Forward Link Transponder and a Return Link Transponder

The satellite was designed to meet four major needs. First, the increasing role of satellite communication in business required smaller dish antennas on the ground. The introduction of higher frequencies (11-14 GHz in the Ku band) became necessary to cater to a larger number of Very Small Aperture Terminals,

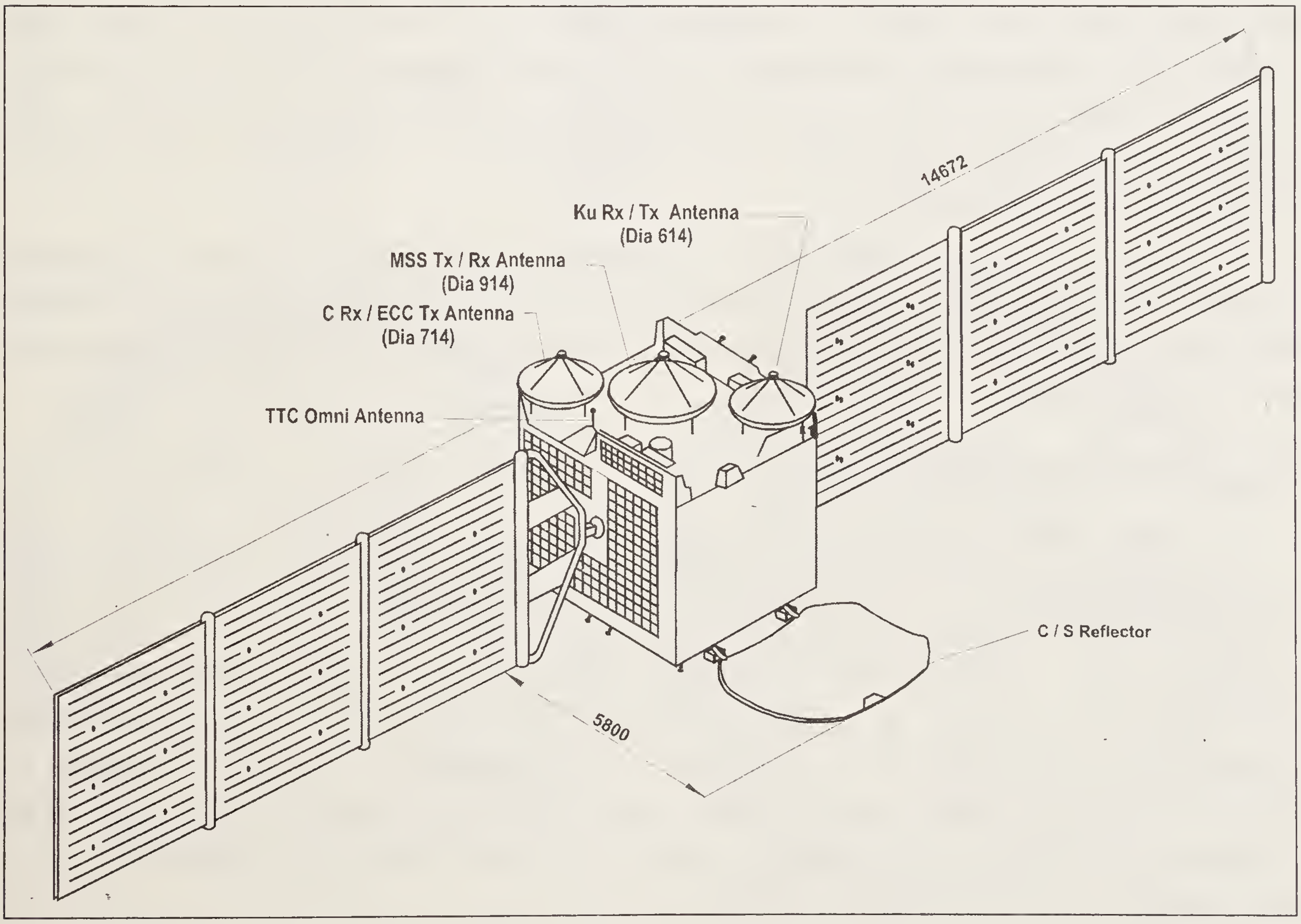


Fig 7.3 : INSAT-2C: Its wide beam covers a vast region from Saudi Arabia to Malaysia. Shaped differently from the first generation series, the satellite offers a wide range of services including mobile communications and access through roof-top antennas.

(VSATs), satellite news gathering (SNG) activities and roof-top antennas. INSAT-2C had Ku band transponders, each of which has 20W of radiated power.

Second, the footprint or the beam of the satellite was not confined to India alone but will cover a wide area from West Asia to Southeast Asia from the satellite's location at 93.5°E (Fig 7.4).

Third, a beginning was made in mobile communication. INSAT-2C provided mobile communication service from the geostationary orbit to the Indian mainland and the adjoining ocean areas.

Fourth, there was a need to increase the power of the output from the satellite and provide a stronger signal. The signal strength is indicated in terms of equivalent isotropic radiated power (EIRP). The term indicates the power radiated by an antenna uniformly in all directions.

With a view to providing the new types of services, INSAT-2C included two 50W transponders for the wide beam, more powerful transponders in the C-band, besides three in the Ku-band.

The power requirements on board the satellite have accordingly increased; the total needed was 1600W as against 1000W in INSAT-2A and 2B. Six solar panels (with two-sided solar arrays) were provided instead of four in the earlier versions. Each and every cell was tested with the help of a Sun-simulator. The satellite incorporated the lessons from the operation of INSAT-2A and 2-B for improving the performance.

Special measures were taken to withstand the impact of solar radiation. Thermal modelling enabled the engineers to provide adequate grounding for absorbing the charges. Similarly, radiation-hardened electronic chips were used to safeguard the built-in memory.

The INTELSAT-INSAT Deal

INTELSAT (International Telecom Organisation) signed an agreement with the Indian Department of Space for leasing 11 transponders on board. INTELSAT handles India's international telecommunication links. The first of a new high-powered series, INTELSAT-VII was deployed over the Indian Ocean Region at 66°E longitude to meet the growing customer needs INSAT-2E for 10 years. The agreement is regarded as a testimony to the reliability and high standard of INSAT's services. This was the first time INTELSAT entered into a deal with a developing country for using the latter's satellite technology. INSAT-2E is in its seventh year of service (2007).

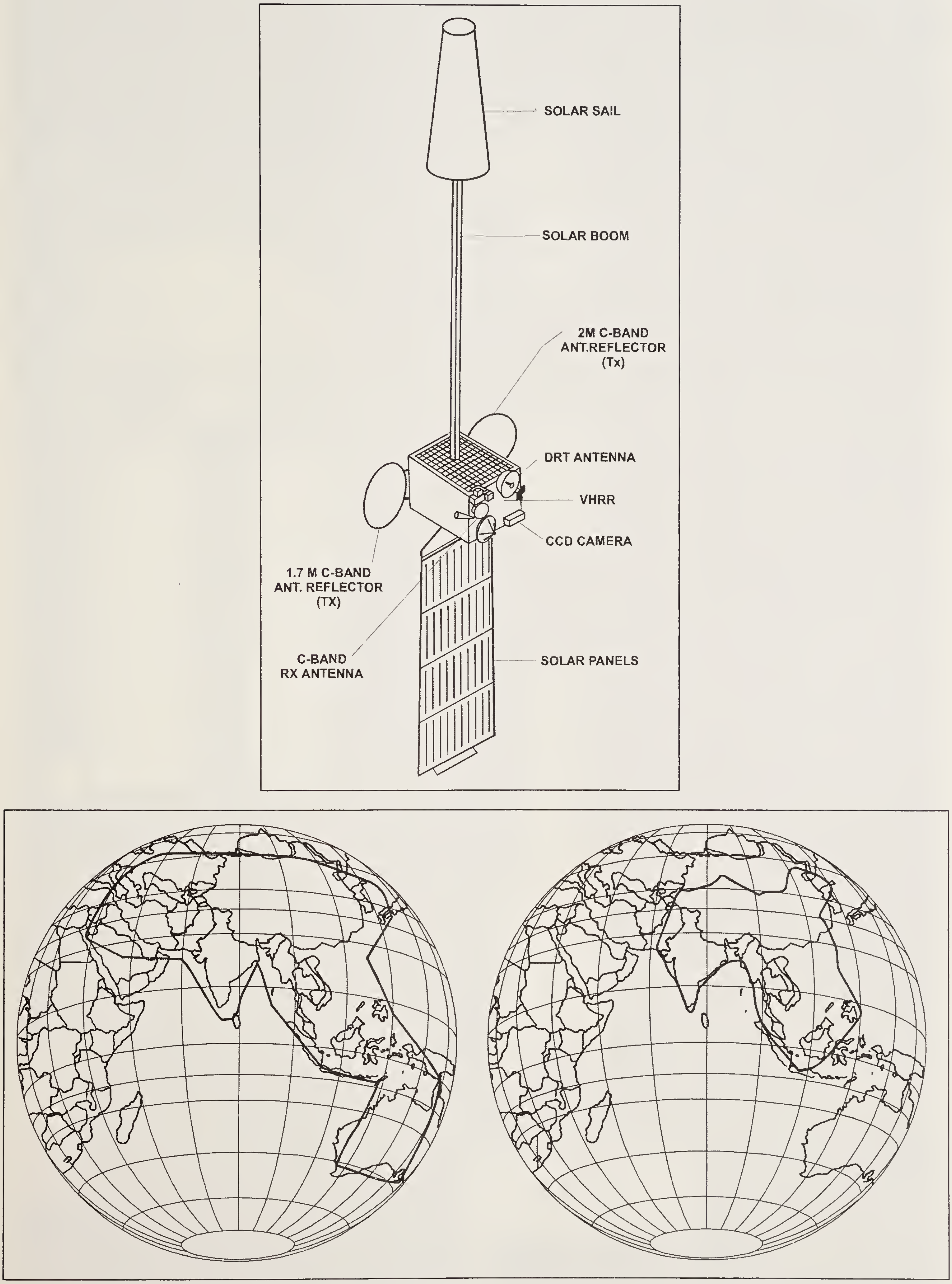


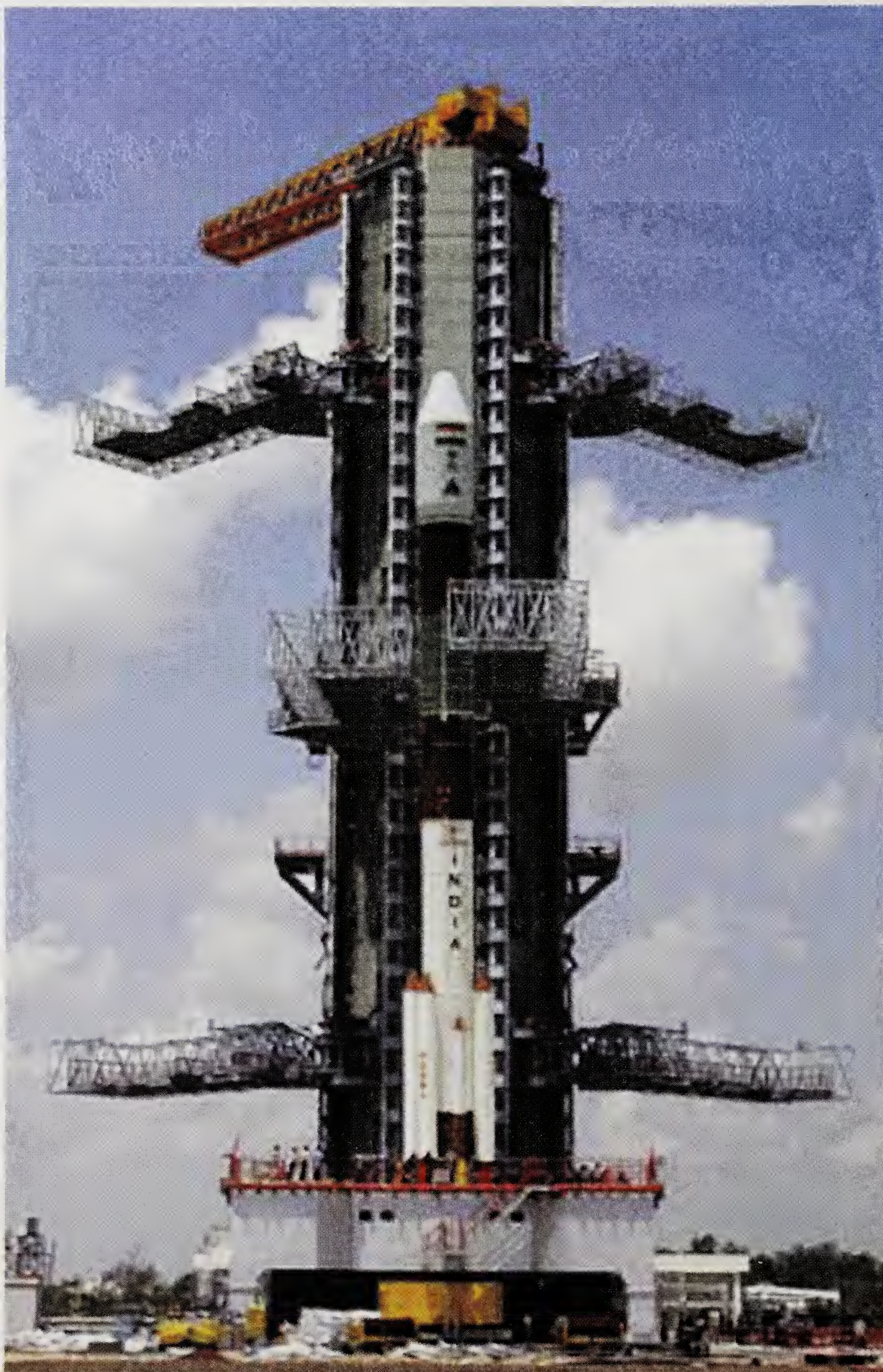
Fig 7.4 : INSAT-2E : The satellite will provide some of its capacity for use by INTELSAT. The meteorological component, not provided in INSAT-2C and 2-D, is included. Wide beam (left) and zonal beam coverage of INSAT 2E for communication links.

The GSAT Series

ISRO has a programme to launch experimental geosynchronous satellites using GSLVs to evaluate new technologies. GSAT-1, launched by a GSLV in 2001, gave an opportunity to test and evaluate many new technologies. There was also an unexpected event. The rocket injected the satellite with a velocity that was 99.4 per cent of the intended 10.2 km/second. Though the shortfall was only 0.6 per cent, it reduced the apogee considerably, though the perigee and the inclination of the satellite to the equator were close to the targeted values. Using satellite's onboard thruster, the orbit of GSAT-1 was raised closed to near-geosynchronous height, with an apogee of 35,665 km and a perigee of 33, 806 km. The inclination was reduced to 0.997 degree. The satellite was put into the 3-axis stabilisation.

The new techniques that were tested included a fast recovery star sensor, which measures the satellite's orientation and quickly recover its "Earth lock" connection to ground stations.

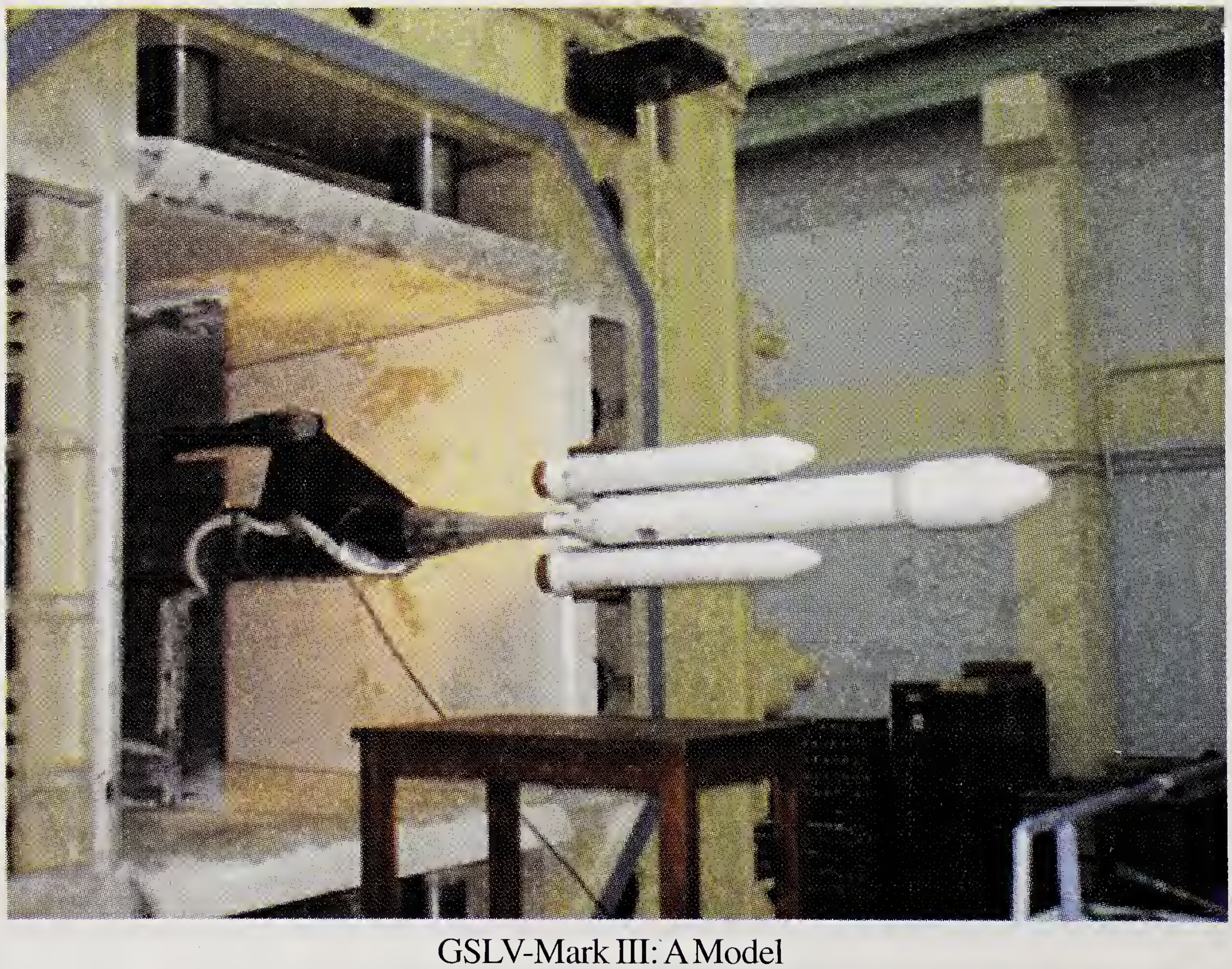
Polar Satellite Launch Vehicle (PSLV): ready for lift-off at Sriharikota



The Second Launching pad at Sriharikota with a PSLV inside

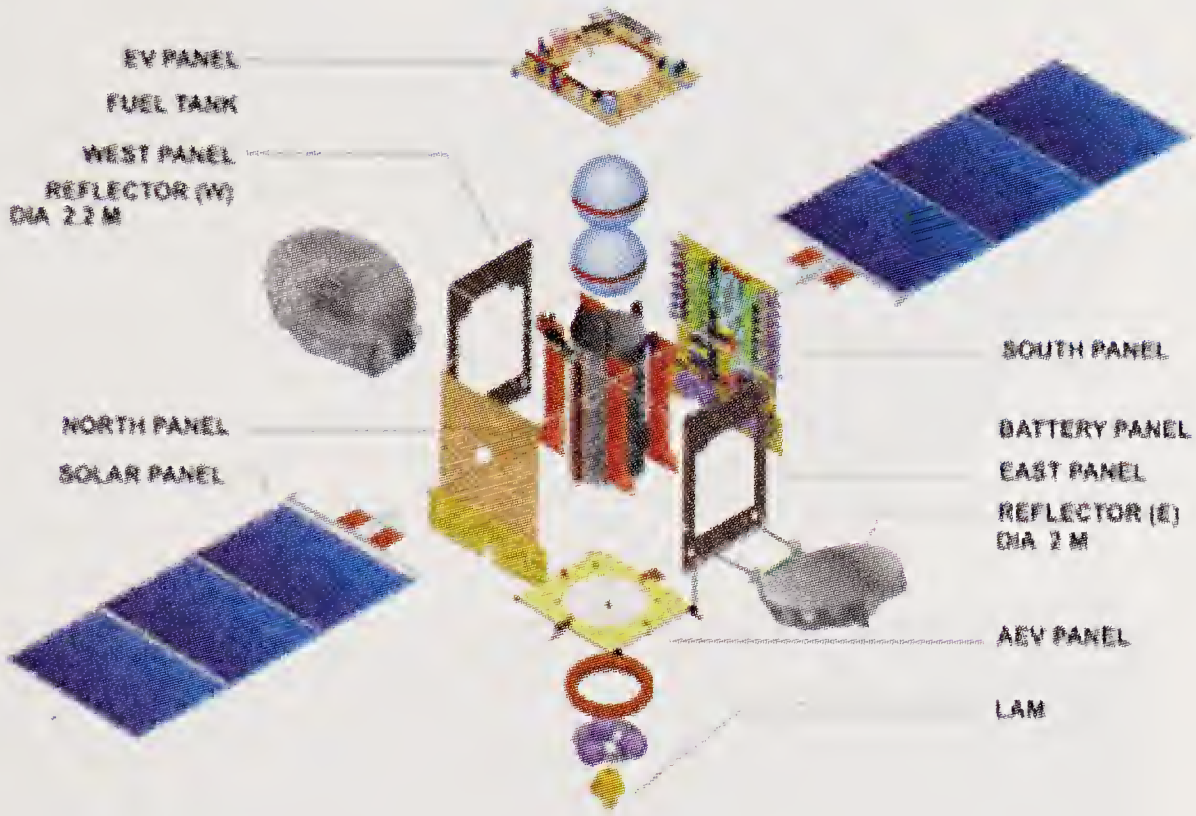
A Geosynchronous Satellite Launch Vehicle (GSLV)

Recovery of a Space Capsule from sea after its orbit



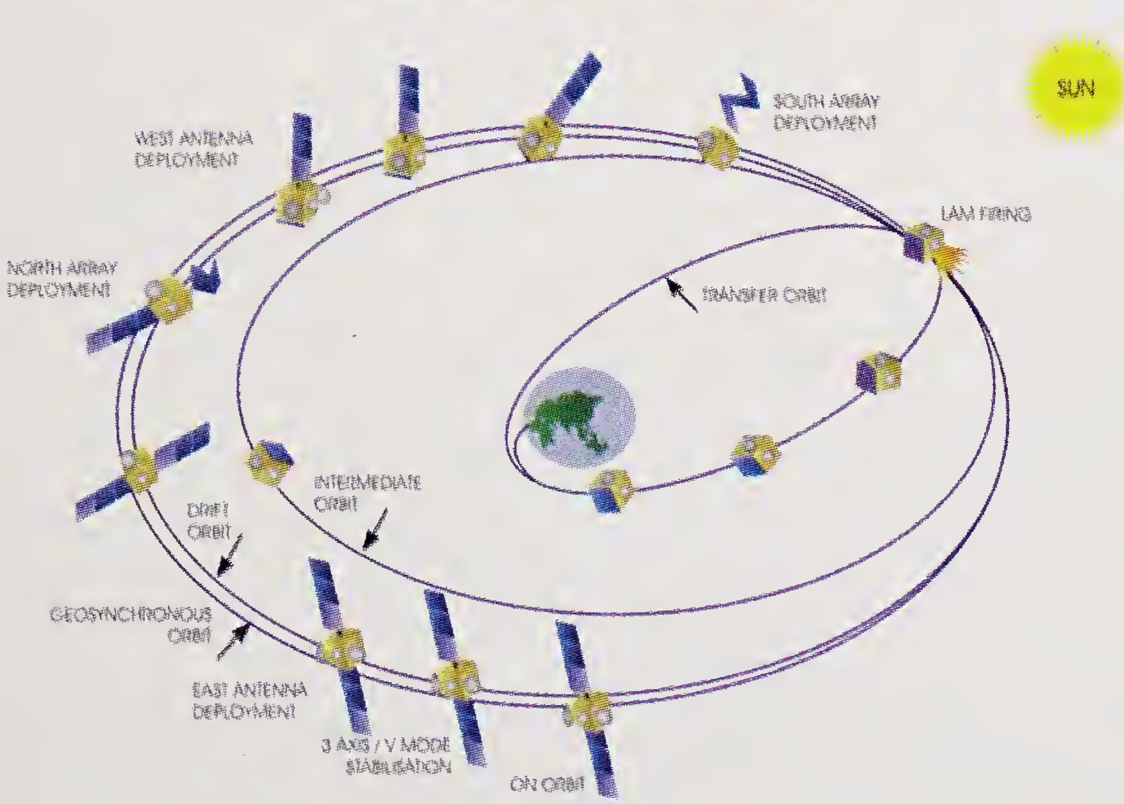
GSLV-Mark III: A Model

INSAT 4-A



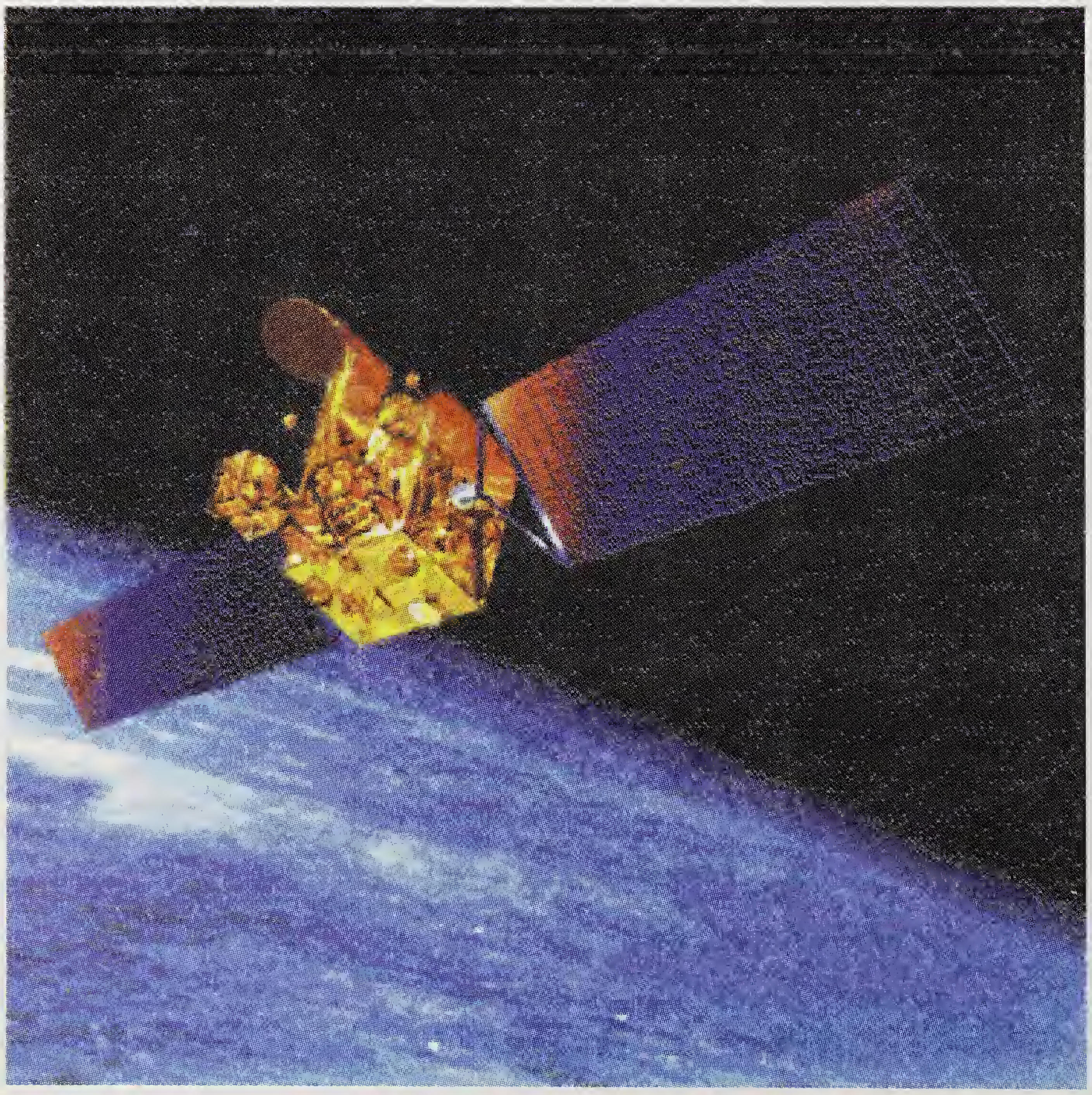
INSAT 4-A Parts

Sequence of Events

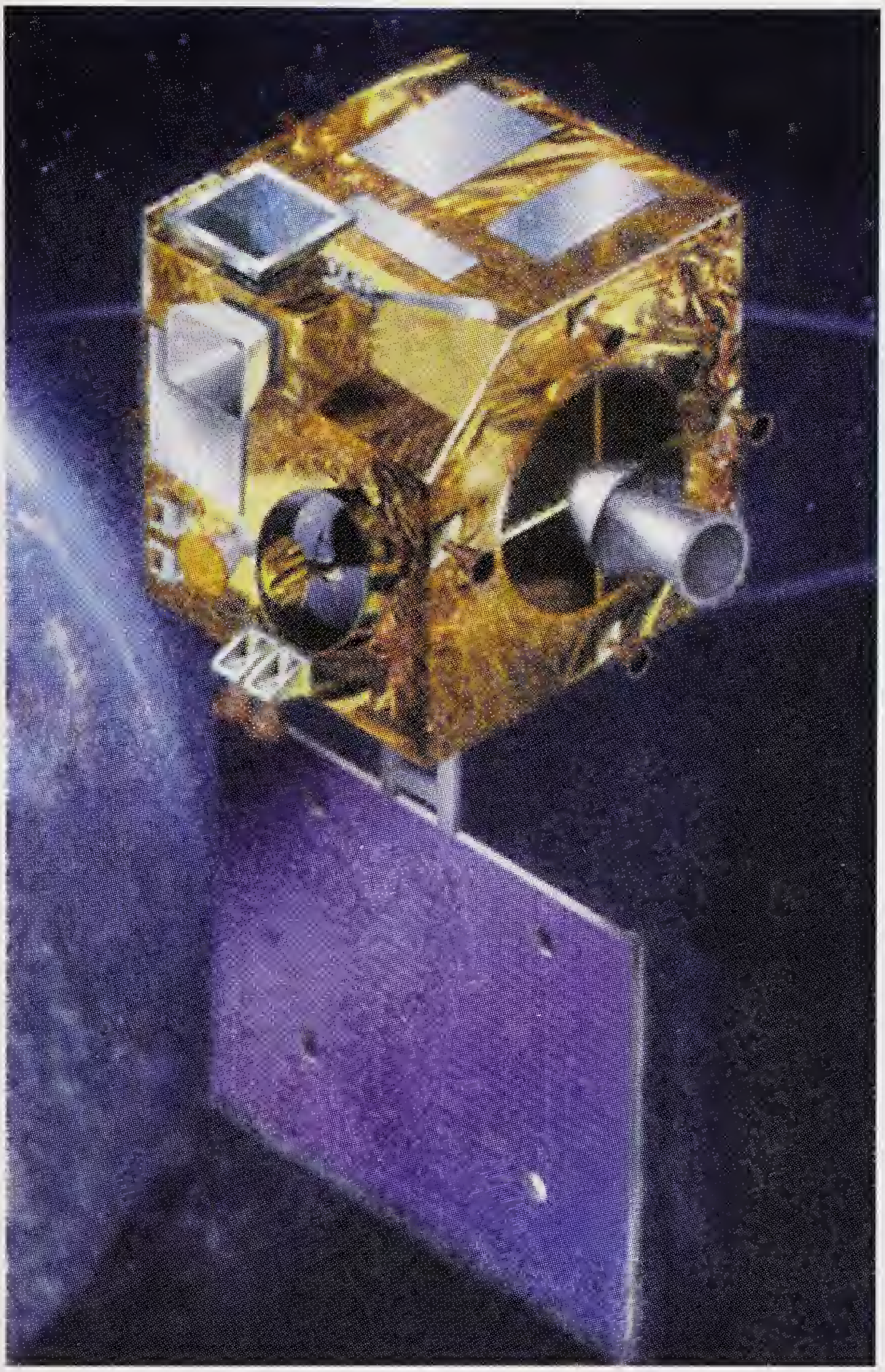


INSAT 4-A Revised GTO

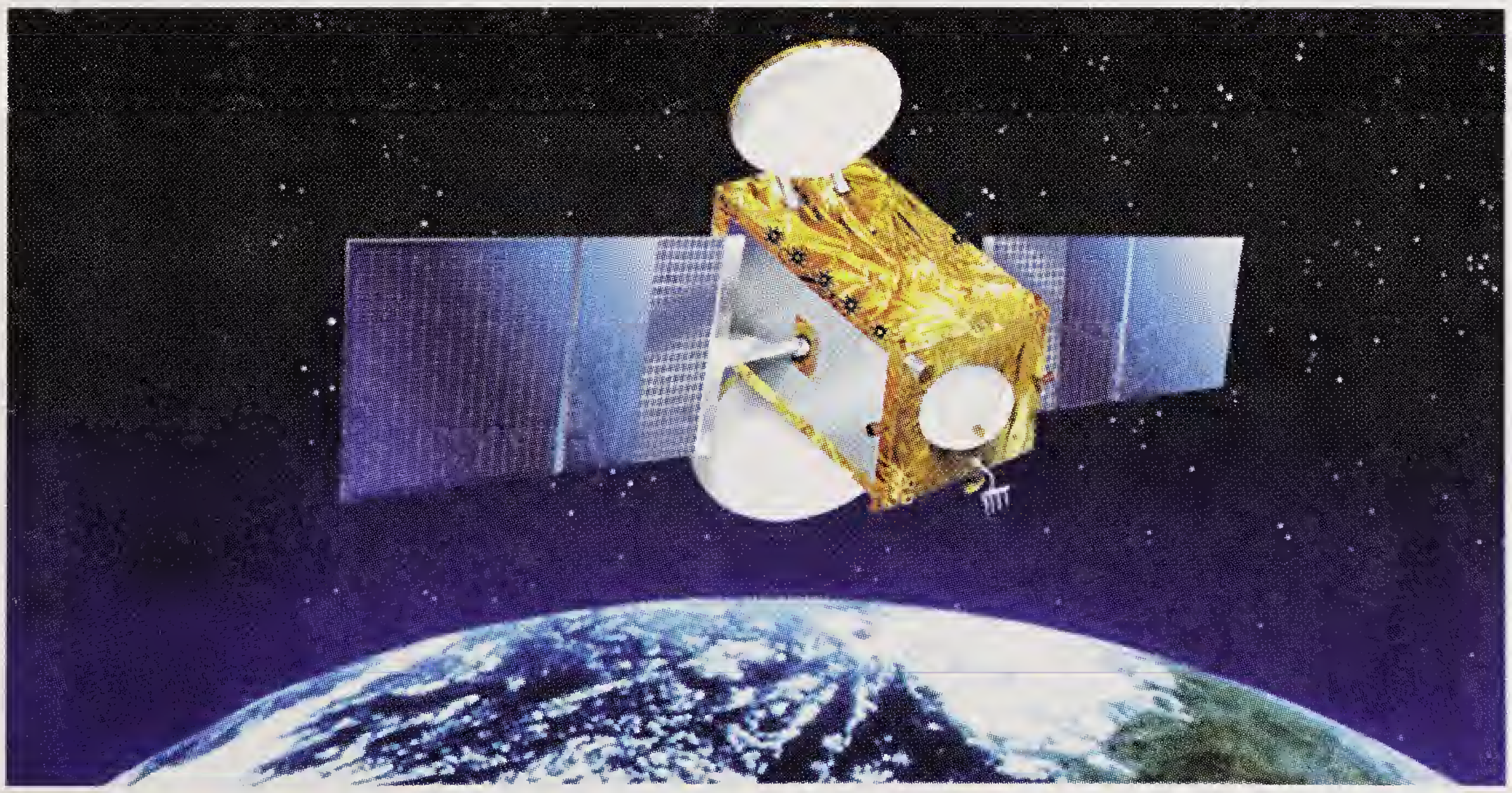
INSAT 4-B



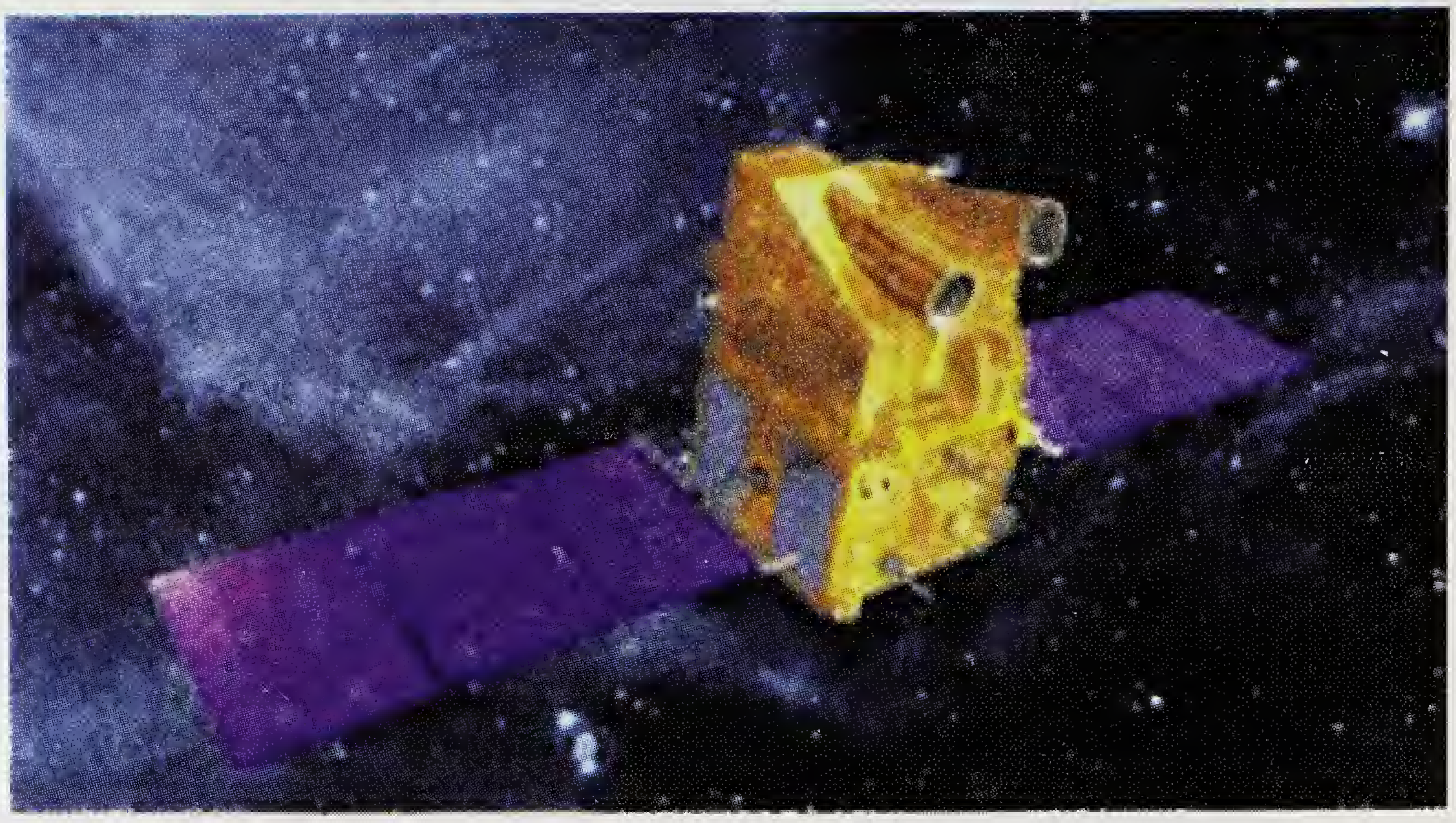
Oceansat-1



Kalpana-1: a weather satellite



EDUSAT for imparting education through satellite



Cartosat-1

3-D view of Jaipur, taken by Cartosat-1

22. More INSATS into Perfect Orbit

Ford Aerospace of USA built all the four satellites of INSAT-1 series as per ISRO's specifications. INSAT-2A, launched into space in July 1992, was the first indigenous INSAT to provide service. INSAT-2A weighed almost twice as much as INSAT-1 and had one and a half times the communications capability and more powerful meteorological instruments. Four more satellites were launched in the INSAT-2 series between 1992 and 1999.

India has the largest domestic communication satellite system in the Asia-Pacific region with ten satellites in service: INSAT-2E, INSAT-3A, INSAT-3B, INSAT-3C, INSAT-3E, GSAT-2, EDUSAT, INSAT-4A, -4B and -4CR. Together, the system provides about 200 transponders in C, Extended C and Ku bands for a variety of communication services. Some of the INSATs also carry instruments for meteorological observation and data-relay for providing meteorological services. KALPANA-1 is an exclusive meteorological satellite.

Four satellites in the INSAT-3 series have been launched and are providing satisfactory service. INSAT-3D (to be launched) is an advanced meteorological satellite. It will have many new technologies including a star sensor that would be flown for the first time in the geosynchronous orbit.

INSAT-3B (2000) inaugurated the third generation series. It provides ku-band (12-18 GHz) transponders that receive and send signals in addition to extended C-band links, besides a mobile satellite services payload. INSAT-3C (2002) carries communications payload without ku-band and a mobile satellite service payload for countrywide coverage. INSAT-3A and -3E were launched in 2003. INSAT-3A has normal C-band and ku-band transponders, as well as a meteorological payload. It carried a Very High Resolution Radiometer capable of imaging in the visible, thermal infrared and water vapour channels, besides a CCD camera. In addition, the satellite has a data relay transponder for links with unattended platforms designed for land and ocean-based automatic collection, and transmission of weather, ocean and hydrological data. INSAT-3A has also satellite-aid search and Rescue payload for India Coverage for relaying signals from distress beacons in sea, air or land. INSAT-3E carries only a communications payload.

INSAT-4A, the heaviest satellite built by ISRO (as of 2005), weighing 3,080 kg, was launched in 2005 from Kourou. The power generated by its two solar arrays is 5500 Watt, the highest so far for an Indian satellite. It has Sun and Earth sensors, momentum wheels, reaction wheels, magnetic torquers and 16 reaction control thrusters for maintaining 3-axis stability.

The satellite has 12 ku-band transponders to provide direct to home TV and other services throughout the country and another 12 C-band transponders for coverage of the country as well as the south-east and north-west regions near India.

The mission sequence of INSAT-4A is the most recent example of the perfection achieved in placing the geosynchronous satellites.

An Ariane rocket inserted INSAT-4A into an egg-shaped orbit with a perigee (the nearest point to the Earth) of 622km and an apogee (the farthest point from the Earth) at 36,152km. (It may be recalled that India's GSLV placed EDUSAT into a perigee of 180km and an apogee of 35,985km). About 30 minutes after the injection into the orbit, the Master Control Facility of ISRO at Hassan took control of the satellite.

The first requirement was simply to orient the satellite to face the Earth and stabilise it by adjusting its gyros. In order to circularise the orbit, additional velocity had to be injected to the satellite by firing the onboard liquid apogee motor (LAM), which is a well-proven workhorse designed and made by India. The first firing of the LAM was done a day later. It raised the perigee to 13,733 km, while the apogee was at 36,008 km. Another essential step was reduction of the inclination of the satellite's orbit to the Earth's equatorial plane from its initial 4.02° to 0.85°. (The final inclination should be zero). The satellite completed its orbit of the Earth in 15 hours and 16 minutes instead of the desired 24 hours. If the apogee occurs over the equator, it would be easy to correct the inclination as well as raise the perigee.

The satellite was then not within the radio visibility of MCF all the time. Hence MCF utilised the assistance of the ground stations of INMARSAT (the international maritime satellite organization) at Beijing, Fucino (Italy) and Lake Cowichan(Canada) as well as ISRO's monitoring station at Biak (Indonesia) to determine the position of INSAT-4A.

The orbital mechanical group, meanwhile, updated their calculations and got ready for the second LAM firing on the 24th. The second firing lasted 42minutes which raised the perigee to 31,479km and reduced the inclination further to 0.12° The orbital period of the spacecraft increased to 22 hours and 13minutes and it was in continuous radio visibility of MCF-Hassan.

Still the orbit was not perfect. A third and final LAM firing was done on Dec 26 for just five minutes and 45 seconds. As a result, INSAT-4A was placed in near-GSO with its perigee at 31,757km and apogee at 36,008km. The solar panels and the antennas that receive and transmit the programmes were deployed.

The satellite was then at 78.1 ° East longitude. It was allowed to drift eastward towards its final location of 83° East. Shortly before it reached the slot, the drift will be arrested to carry out certain in-orbit tests at 81.5°E. It would then be collocated with INSAT-2E and INSAT-3B. INSAT-3C,EDUSAT and Kalpana (weather satellite) are also collocated at 74°E. The colocation and operation without interference are significant achievements.

It is appropriate to recall that ISRO started its design and fabrication of the apogee motor even by 1980. In 1981, when the Ariane Passenger Payload Experiment (APPLE) was launched, ISRO put its apogee motor into orbit. It was a solid propellant motor (an improvised version of the fourth stage of SLV-3, India's first rocket that carried a satellite), as the liquid rocket was developed only later. The motor could not be switched off and on once it was ignited. Thus there was just one chance to make the elliptical orbit circular. It was a maiden effort but it worked very well, much to the understandable disbelief of foreign experts. It was an incredible achievement by any standard. The first orbit had a perigee of 201km and an apogee of 36,206kmwith an inclination of 10.5° and an orbital time of 10hours and 39.8 minutes

The apogee boost motor, as it was called had a capacity for providing a velocity increment of 1530metres a second to a mass of 630kg in the transfer orbit. But the weight of APPLE increased to 673kg at lift-off and so the velocity increment after the apogee motor firing was limited to 1440m/sec. This resulted in a near-22 hour orbit and the additional velocity needed to make it a 24- hour orbit was provided by the 16 hydrazine thrusters on board.

The ISRO engineers who dared to do this risked their credibility and career. They were among our pioneers, whose courage and skill deserve a special mention in the history of India's space endeavour. INSAT-4A's entry into a perfect orbit is but a continuation of this tradition.

INSAT-4B, identical to INSAT-4A and -4CR (which replaced INSAT-4C, lost in the failed GSLV mission), were launched in 2007. Future launches will include INSAT-3D, an advanced weather satellite, and INSATs D to G. INSAT-4G is expected to carry a satellite air navigation payload.

23. Sensors and Controls

The stability in space is disturbed by the Earth's magnetic field, the gravitational field and solar radiation etc. Most of these disturbances occur cyclically during each orbit of a satellite. These are corrected by reaction wheels. The other means of correction viz., control rockets that need fuel to operate, can be used sparingly, should the wheels prove inadequate in correcting the disturbances.

A satellite must remain steady in orbit so that the onboard camera, for instance, can take pictures without jitter. In a three-axis stabilised satellite system, reaction wheels provide high pointing accuracy, low jitter and long-term attitude stability.

Reaction wheels are rotated typically at around 2500 revolutions per minute (rpm). The rotating wheel exerts an equal and opposite torque on the satellite, which starts rotating as a reaction, following Newton's Third Law. If the wheel is slowed down, the satellite's rotation is reversed. Three reaction wheels can thus control the rotations about the pitch, yaw and roll axes, respectively. A fourth one is kept as a standby. When all three axes are controlled by reaction wheels, it is called zero momentum stabilisation.

Satellites (e.g. INSATs) in geosynchronous orbit have, in addition to reaction wheels, momentum wheels which are larger and heavier and are rotated at about 4000-12,000 revolutions per minute (rpm). Typically a geosynchronous satellite has two momentum wheels and one reaction wheel. A momentum wheel rotates only in one direction, while a reaction wheel can rotate in either direction.

When momentum wheels are operated to provide stability to one axis, it is called biased momentum. Sometimes it becomes necessary to dump the extra momentum acquired by the momentum wheels. Magnetic coils on board a satellite are used to cause a torque and release the unwanted momentum. Liquid reaction control rockets (bipropellant thrusters) are used as and when needed to correct larger deviations.

The reaction wheel assembly consists of a reaction wheel, wheel drive electronics and the interface electronics. The wheel drive electronics gives the signals for accelerating or decelerating the wheel in the required direction.

The wheels have been ground-tested for over 20,000 hours and they have been successfully used in Indian remote sensing and communication satellites – IRS and INSAT-2 series. The reaction wheel technology is derived from that of momentum wheel, also designed and fabricated in India for the APPLE spacecraft.

The pointing accuracy of IRS 1A/1B is 0.4° about its roll and pitch axes, while for IRS-1C it is 0.15°. The yaw axis accuracy is also improved from 0.5° for IRS-1A/1B to 0.2° for IRS-1C.

While its Earth sensors indicate the location of the Earth correctly and ensures the satellite's stability in the long run, their accuracy in the short run may be affected by the seasonal differences in the Earth's radiance (due to snow etc). Gyroscopes are therefore used to ensure stability in the short run. The long-term drift of the gyros is corrected.

The introduction of an improved sensor has made a big difference in determining the accuracy of the orbit after the actual parameters of the orbit are known. The accuracy of the attitude determination for IRS-1C is 0.01° with the star sensor.

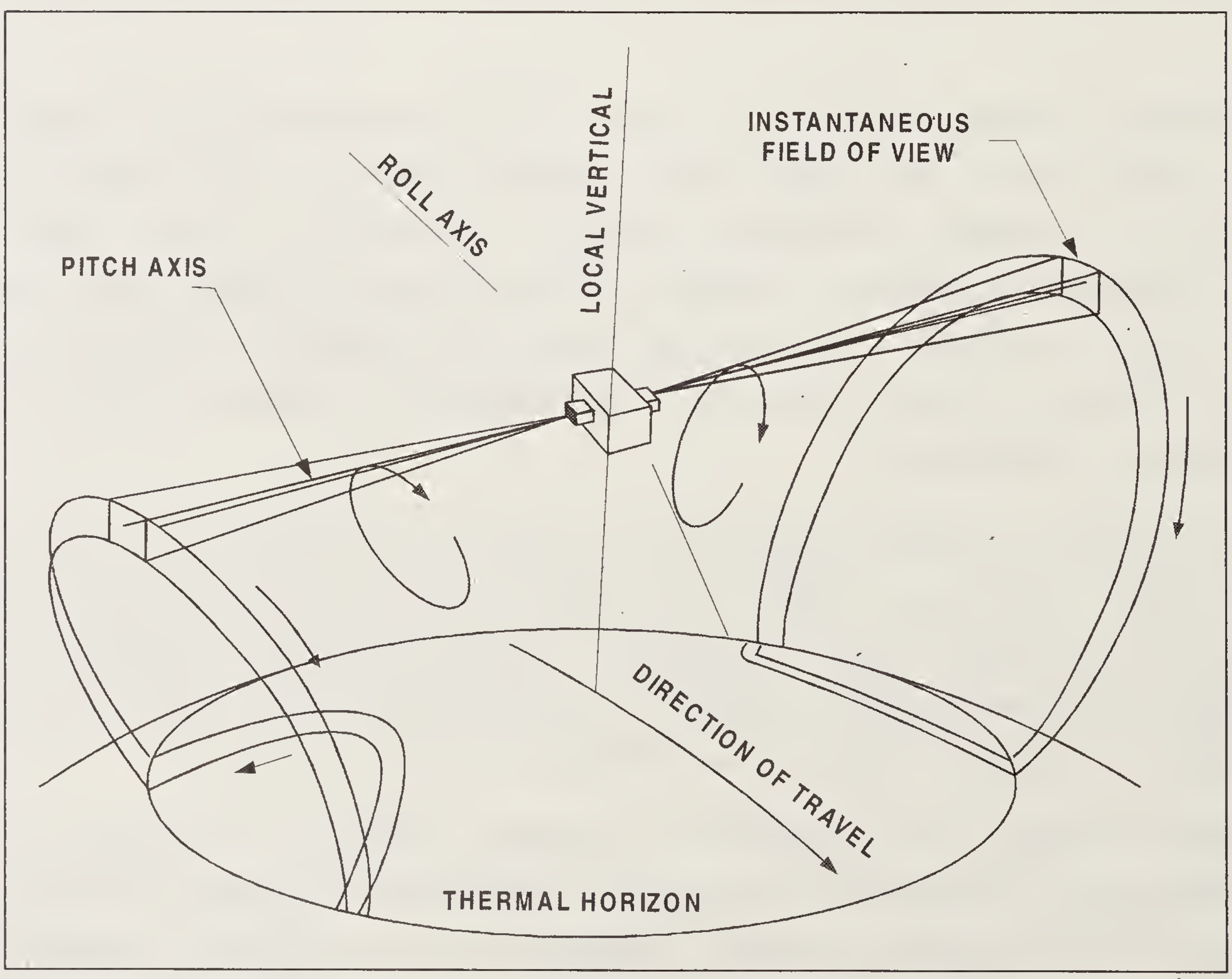


Fig 7.5 : Conical Scanning Earth sensor, used for attitude sensing of 3-axis stabilised satellites at a wide range of altitudes. The infrared detector senses the change in radiance from space to Earth and vice versa.

Each INSAT has two momentum wheels and one reaction wheel. In the on-orbit mode, both the momentum wheels are simultaneously rotated to provide gyroscopic stability to the pitch axis. If one wheel fails, the reaction wheel (kept at 90° to the other wheel) is used to compensate for the loss of momentum to a large extent. By varying the speeds of momentum wheels, the pitch axis can be controlled and deviations in the East-West and North-South directions can be corrected. Beyond a certain limit, onboard thrusters are fired for corrections.

As the momentum wheels are kept in a V configuration, the benefit of stability is available to the roll and yaw axes also, as they get interchanged every six hours during the satellite's orbit around the Earth.

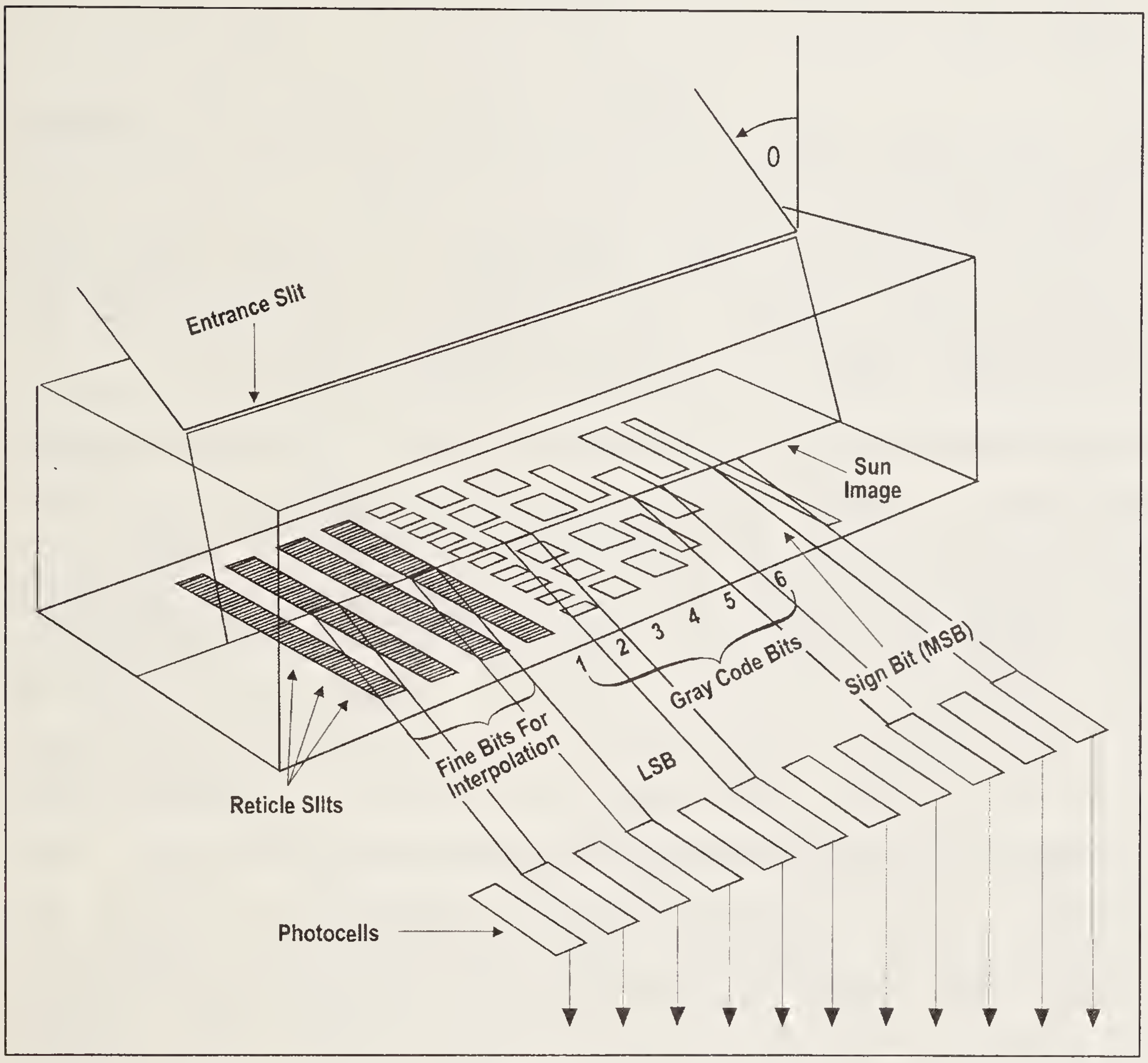


Fig 7.6 : Digital Sun Sensor, useful for a satellite to attain and maintain its correct orbit.

Earth Sensors

Earth sensors, Sun sensors and star sensors play a critical role in keeping the satellites in the correct orbit and in maintaining the payloads in a steady state. The reaction control systems act on the basis of errors detected by the sensors.

Infrared Earth horizon sensors of various types have been used in the Indian satellites e.g. a conical Earth sensor is used for sensing the attitude of a three-axis stabilised satellite. When the satellite's field of view of the scan path intersects the Earth's disc, the detector senses the change in radiance from space to Earth and again to space. The temperature of the Earth (300K) is sharply at variance with that of space (3K). The time difference between the two crossover points is processed and compared with a scan reference signal. The errors, if any, in the roll and pitch axes are calculated. A filter restricts the incoming radiation to the 14-16 micrometre band of the Earth's atmosphere. Hence, the sensor is not affected by the Sun or the Moon in the field of view (Fig 7.5).

An Earth sensor on a geosynchronous satellite views the Earth from 36,000 km. The Earth's disc at this distance has an apparent diameter of 17.3°. From the geosynchronous orbit, an oscillatory Earth sensor detects the characteristic radiation of the Earth's atmosphere to locate the horizon. This sensor indicates

the roll and pitch errors of satellites. The accuracy of the sensor is high, about 0.03°. Spurious signals from the satellite itself are cut off. Onboard correction systems take care of systematic errors due to the Earth's oblateness, radiance and temperature.

Sun Sensors

The Sun, being a very bright object, is the most common source of direction for satellites. A Sun sensor measures the Sun angle with reference to the satellite.

Several types of Sun sensors have been developed. An analog Sun sensor is used for pointing one of the satellite axes towards the Sun and also for continuously pointing the solar panels in the Sun's direction (Fig 7.6).

In the geostationary transfer orbit, a digital Sun sensor is used to measure the Sun angle with reference to satellite's pitch axis. For example, seven minutes after an INSAT is injected into space, both the digital Sun sensors indicate the Sun's presence. In the Sun-pointing mode, the roll and yaw errors are indicated. A narrow slit permits sunlight as a thin line. Inside the Sun sensor, the light is passed through several transparent and opaque windows, illuminating a series of solar cells. For every 0.125° change of Sun angle, a unique pattern is illuminated and it is coded as Sun sensor output. The digital Sun sensor can be used until the satellite is oriented towards the Earth during the geosynchronous transfer orbit.

Another sensor called coarse analog Sun sensor is designed to support Sun acquisition in the transfer orbit, though a contingency for it has never arisen. In the on-orbit mode, the sensor is designed to compute the yaw error. The expected sensor output for different satellite local times as well as the yaw errors are predicted in advance.

Yet another device has a set of four Sun sensors and serves as a fire brigade for use in emergencies. Though it has limited accuracy, it can detect errors in all the three axes and determine the spacecraft's orientation.

The IRS satellites use precision Sun sensor which can help in orienting the yaw axis. The sensor has an accuracy of 0.05° with regard to center of the Sun's disc. The IRS has also five Sun sensors to measure the angle between the Sun vector with respect to two axes. The sensor is used for spacecraft acquisition and for line corrections. There are also twin-slit Sun sensors, mainly used in spinning satellites to measure the angle between the Sun and the satellite spin axis.

Star Sensors

Stars are the most accurate reference sources for finding direction, since they appear as point sources. Star mappers scan the entire sky and can sense

1500 stars up to the fifth magnitude. The attitude is computed by knowing the position of each of the sensed stars. The other type of star sensors called star trackers, generally track one star in the field of view for a long time. The sensors on IRS-1A and 1B, for example, scan the sky in an 8° wide path belt using the orbital motion of the satellite. An advanced star sensor has been developed; it can identify a star by comparing it with a star catalog on board and can compute the attitude of the satellite.

Yet another type of sensor is called the landmark sensor. Rohini-D1 and D2 satellites had an experimental sensor (consisting of two TV cameras working in visible and near infrared bands) to detect landmarks and determine the attitude. Rohini-D2 had an additional feature: it could compare two imageries taken in different spectral bands and transmit a classified imagery along with one of the selected imageries. It was aptly called a smart sensor!

The Laboratory for Electro-Optic Systems of the ISRO Satellite Centre, Bangalore has developed various types of sensors and optical systems. The laboratory's facilities include simulators that mimic the Sun, the Earth, and some stars.

Gyroscopes

In addition to sensors, all satellites need gyroscopes to keep them stable in orbit. The gyroscope has been in use for over a hundred years. It was first installed in a ship around 1910. Its use in rockets started with the German V2 during World War II. Several advances have since been incorporated into the device.

The gyro functions like a spinning top balanced on a spring. A spinning body tends to keep its spin axis pointed in a constant direction. For instance, the Earth keeps its polar axis aimed at the North star. A gyro is but a spinning mass. The axis around which the mass spins resists any torques. When a torque is applied to the gyro, the spinning mass starts to precess around an axis perpendicular to the direction of the applied torque and spin axis. The rotation of the spinning axis about the vertical is known as precession. Precession is used to measure the angular velocity of the spacecraft around its three axes.

It is particularly useful in a low-Earth orbit satellite, since the yaw orientation of the satellite cannot be determined by Earth sensors, which can detect only pitch and roll orientation. In IRS-1A two gyros, known as dynamically tuned gyros (so-called because of the in-built arrangement that cancels the dynamic disturbances in the orbit), are placed in such a way that they can measure the changes in a satellite's yaw axis. Some redundancy is built in. The spinning mass is driven by a motor that rotates at 6,000 revolutions per minute.

The gyro is free from unwanted disturbances at the base. The gyro is suspended on high-precision ball bearings with special indigenous lubrication that lasts for some years in space.

Every gyro indicates some drift away from the originally designed path – an inevitable feature due to manufacturing limitation. The nominal drift rate is measured in terms of degrees per hour. The actual drift rate is measured and corrected at every half orbit with reference to the position of the Sun. The drift is corrected using the Sun, star and Earth sensors. IRS-1C, for example, has three gyroscopes, one for each of the axes, in view of the extra stability required for achieving a ground resolution of less than six metres in its imageries. The INSAT-2 series has also three gyroscopes.

ISRO's Inertial Systems Unit has developed and fabricated the gyroscopes, as well as reaction wheels and momentum wheels.

Solar Array Drive

Another device that calls for precise and reliable control is the solar array drive mechanism. The solar arrays should be kept rotating suitably towards the Sun so that maximum power is generated. Based on the information from Sun sensors mounted on the arrays, the panels can be rotated at different rates. Initially after their deployment, the panels should be oriented to track the Sun. Hence, the panels are rotated fast (at 0.5°/s) and once they acquire the Sun, the orbital rate becomes normal, i.e. one rotation in 103 minutes. In other words, the solar array drive will rotate 360° in each orbit. No rotation is done when the cameras are operated. The drive motor of the array completes one rotation in 720 steps. Even when no power is used, the arrays are kept in position by torques provided by magnetic circuits. The solar array drive is used in the IRS series.

Controls in Rockets

Reaction control system packages for launch vehicles (SLV, ASLV and PSLV) have been designed and made indigenously. There are three main types of control systems: the secondary injection thrust vector control (SITVC), bipropellant reaction control systems and monopropellant reaction control systems (RCS). The SITVC system is based on injection of strontium perchlorate into the supersonic exhaust of the rocket motor to produce a side thrust. Reaction control systems have bipropellant or monopropellant (hydrazine) engines of various capacity ranging from 3000 Newton (N) to 10 N. The propellants are hydrazine and red-fuming nitric acid.

In the first stage of PSLV, for example, pitch and yaw control is achieved by the injection of strontium perchlorate. RCS for the first stage operates in a

system using Earth storable hypergolic propellants (nitrogen tetroxide and monomethyl hydrazine). The SITVC system is used in the strapon motors to augment the control forces provided by the RCS. In the ASLV, the RCS in the first and third stages use hydrazine.

An autonomous control system is in each of the three stages. All the four strapon rockets of the first stage have what is known as engine gimbal controls for pitch, yaw and roll axis stability. The second stage has such engines for pitch and yaw control and a reaction control system for roll control. The third stage has two engines that can swivel during the thrust phase and a cold gas system for the coasting phase (when the engine is off).

An inertial guidance system on the first stage will be in overall control.

Pressure Transducers

A vital component in all stages of ASLV, PSLV, GSLV, SROSS, IRS and INSAT, is the pressure transducer. It is an electromechanical device that converts pressure into proportional electrical output. The transducers are miniature in size and are space qualified. The pressure ranges sensed vary from 0.3 bar to 0.333 bar.

The technical know-how to make them was acquired from France during 1974-75. According to the agreement, with the French agency (Society Europeenne de Propulsion-SEP) 8000 pressure transducers were manufactured and exported to SEP to be used in Ariane launch vehicles. The contract was completed in 1983. Based on the experience, LPSC carried out studies on the development of special transducers for monitoring the pressure difference between the fuel/oxider lines in liquid stages of launch vehicles. The transducers were used in the second and fourth stages of PSLV.

LPSC Bangalore developed pressure and temperature transducers for the cryogenic stages of GSLV. Pressure transducers are required in large quantities for Defence, R&D laboratories and process industries. LPSC has transferred the technology to Indian industries, while continuing with the development of special transducers for the space programme.

Control Engines

Raising the orbit of IRS and SROSS series of spacecraft as well as control of their attitude and orbit are done by their propulsion system that works on the monopropellant, hydrazine. The system has one-Newton (N) engines, besides propellant tanks, filters, pressure transducers and other components. N (Newton) is a unit of force, which produces on a one kg of mass an acceleration of one metre per second every second.

Hydrazine is thermally decomposed into hot gases which are then expanded and expelled through a nozzle to produce the control forces. The engines are capable of operating for very short periods (e.g. 30 milliseconds) as well as for long periods (e.g. 10,000 seconds).

For example, 16 one-Newton engines and related components were installed in IRS-1A and 1B. A total of 80 kg hydrazine was stored in four tanks and it was designed to last three years. In view of the good stability in orbit, the satellites continued to function for a much longer period. IRS-1C has a 11N hydrazine thruster in addition to smaller thrusters (1N engines).

For satellites in the GEO such as INSAT, bipropellant systems are used for orbit raising and attitude and orbit control. A special requirement of satellites in GEO is the liquid apogee motor (LAM) that is used for raising the orbit of the spacecraft from the transfer orbit to a GEO of 36,000 km. For LAM as well as attitude and orbit control engines, a combination of monomethyl hydrazine (MMH) and mixed oxides of nitrogen (MON-3) is used. MMH is stored in two tanks and MON-3 in one. Helium, which is used to exert pressure on the propellant is stored in two gas tanks.

During orbit raising, high-pressure helium is regulated from 235 bar to 16 bar. The LAM engine is more powerful (440N) than the attitude and orbit control engines (AOCs) viz. eight 10N and another eight 22N bipropellant thrusters.

Electronic Systems

Electronics plays a key role in tracking, telemetry and telecommand. Electronic devices also regulate a wide range of functions from simple power supplies to sophisticated guidance and control. The systems must be light, and compact. Right from the early days of sounding rockets, telemetry and telecommand systems were developed indigenously.

A telemetry package is an assembly of small gadgets on board a rocket or satellite consisting of transducers, signal processing units, amplifiers, voltage regulators, and a transmitter. Transducers measure various parameters such as thrust, pressure and vibration. In accordance with the data measured by them, transducers put out analogous voltage. An oscillator whose frequency is controlled by the voltages, puts out corresponding signals which are amplified and put in the allotted frequencies. Onboard transmitters beam them to ground antennas. Electronic devices have been made to receive and process the signals. With the coming of multi-stage rockets, onboard electronics was designed to do other complex jobs such as timing the ignition of a rocket motor or stage separation and steering the rockets along the prescribed path. The challenging task of making indigenous gyroscopes and accelerometers was accomplished successfully.

Packaging electronic devices into a small volume of space inside a rocket poses the problem of mutual interference among them. Just as the ignition of a car in the neighbourhood may produce streaks on the TV screen, electromagnetic interference may cause problems in electronic equipment. Measurements are therefore made to ensure that the rocket or satellite does not cause any interference problems or be affected by their electromagnetic environment.

Frequency reuse is another area where state of art technique have been incorporated. The same frequency can be used in different areas for transmitting different messages through spot beams instead of one common beam. Another method is based on the nature of the electromagnetic wave, which consists of oscillating electric and magnetic field vectors, perpendicular to each other and each perpendicular to the direction of propagation of the wave. Based on this feature, a two-fold frequency reuse can be achieved by what is known as polarisation discrimination, which is based on polarising electromagnetic waves in different directions, with suitable antenna design.

24. Master Control at Work

India's expertise in controlling satellites in orbit is internationally recognised as one of the best in the world. The control operation of INSATs, which relay television programmes to your sets is done at the Master Control Facility (MCF) of the Indian Satellite Research Organisation (ISRO), located at Hassan in Karnataka.

The operations at MCF are carried out in two phases. The first starts from the time of injection of a satellite into the egg-shaped geosynchronous transfer orbit and lasts until it is fully deployed and placed in the allotted slot in the circular geosynchronous orbit, which is 36 000km above the equator. The second phase starts after the satellite is declared ready for use.

The first phase calls for some critical operations such as firing of the onboard rockets to raise the orbit, deploying the antenna and solar panels, switching on the momentum wheels designed to give stability using the Earth and sun sensors, besides testing the payload. Engineers from various ISRO centres and MCF carry out these manoeuvers.

MCF controls all of ISRO's geosynchronous satellites—INSAT-2E, INSAT-3A, -3B, -3C and –3E, INSAT-4A, 4B and -4CR, besides, Kalpana (weather satellite), GSAT-2 and GSAT-3 (called EDUSAT). It is significant that all of them have been launched after 1999. With a design life of 10 to 12 years, they would need maintenance for quite some time. Moreover, by 2010, MCF is expected to be in control of 20 satellites in the geosynchronous orbit (GSO). And the satellites would be fully loaded and used.

Of the 165 satellite-based TV channels in India, as many as 83 channels and news feeds (51 for Doordarshan and 32 for private operators) are operated on INSAT satellites. The satellites provide for 24-hour broadcasts (25 channels for Doordarshan alone) as well as news feeds from different parts of India as required. Moreover, there are over 40,000 very small terminals, called VSATs, all over the country linking with the satellites for various purposes. In sum, 20 per cent of the country's economic activity is carried out through INSATs.

Given this order of heavy user demand, even a few seconds of disruption in services cannot be tolerated. The health of the satellites has to be closely watched and their functions maintained round the clock.

The average age of the controllers is only 37. They often take split-second decisions based on a mastery of orbital mechanics. The operations are done in three shifts and the sequence of the shifts has been carefully chosen in accordance with the modern medical findings on biological rhythms to ensure the highest level of alert without any adverse effect on the staff.

About 100 computers are interconnected to process the real time data from the communications satellites simultaneously. Each satellite's status and activities are automatically displayed on the screen in a colour-coded manner, extending to 100 pages, each with 20 lines showing some 2000 parameters (like pressure, temperature, attitude etc.). The controllers closely watch some 200 (out of 800) parameters and select the critical ones depending on the situation. The computers themselves can correct some of the deviations, while giving audio and video signals to alert the engineers. The controllers would wait only for 90 seconds to make sure that the signals are not spurious, before getting ready for action. The corrections get done at various levels, depending on the problem. None is allowed to do anything without knowing the consequence of the move, as there are only a few seconds between success and disaster. The expected signatures and the instructions to deal with them have all been elaborately laid down. It is only when a problem persists, simulations are done with the help of experts in and out of MCF.

The commands sent to a satellite vary in number and nature from a handful to a couple of hundreds, as called for by the intended operations. The experts, for example, calculate on each occasion the duration of the firing of the thrusters (which can operate over a wide range from 16 milliseconds to several minutes), and confirm that their commands are carried out. The software to convert the signals into data that can be displayed on the computers has been developed by ISAC, and is being maintained by MCF. Also, MCF itself has developed many software utilities which will help them to handle various health situations of the satellites. Senior executives could be at the controls within five minutes and even as they reach, they can phone in instructions.

The worst nightmare scenario for them is what is known as the loss of the Earth lock, which means the satellite is no longer pointing towards the Earth, which calls for action within seconds. In such a situation, the first concern would be to preserve the satellite's power and propellant and putting it on a safe mode. For instance, in January, 2007, solar disturbances led to the loss of INSAT-4A's Earth lock. MCF engineers immediately fixed the problem in stabilising the satellite within 30 minutes.

The positioning operations of EDUSAT, launched from Sriharikota well brought out the challenge involved in this field. The satellite, which was 200km below the GSO after the three apogee rocket firings, was allowed to drift at 2.55° a

day from 56° E longitude; the drift was progressively reduced by raising the satellite's orbit to approximate the GSO and finally the satellite was positioned at the intermediate location of 70.7°E (Fig 7.7). After completing the in-orbit testing of the antenna over six days, the satellite was lowered by 39km and

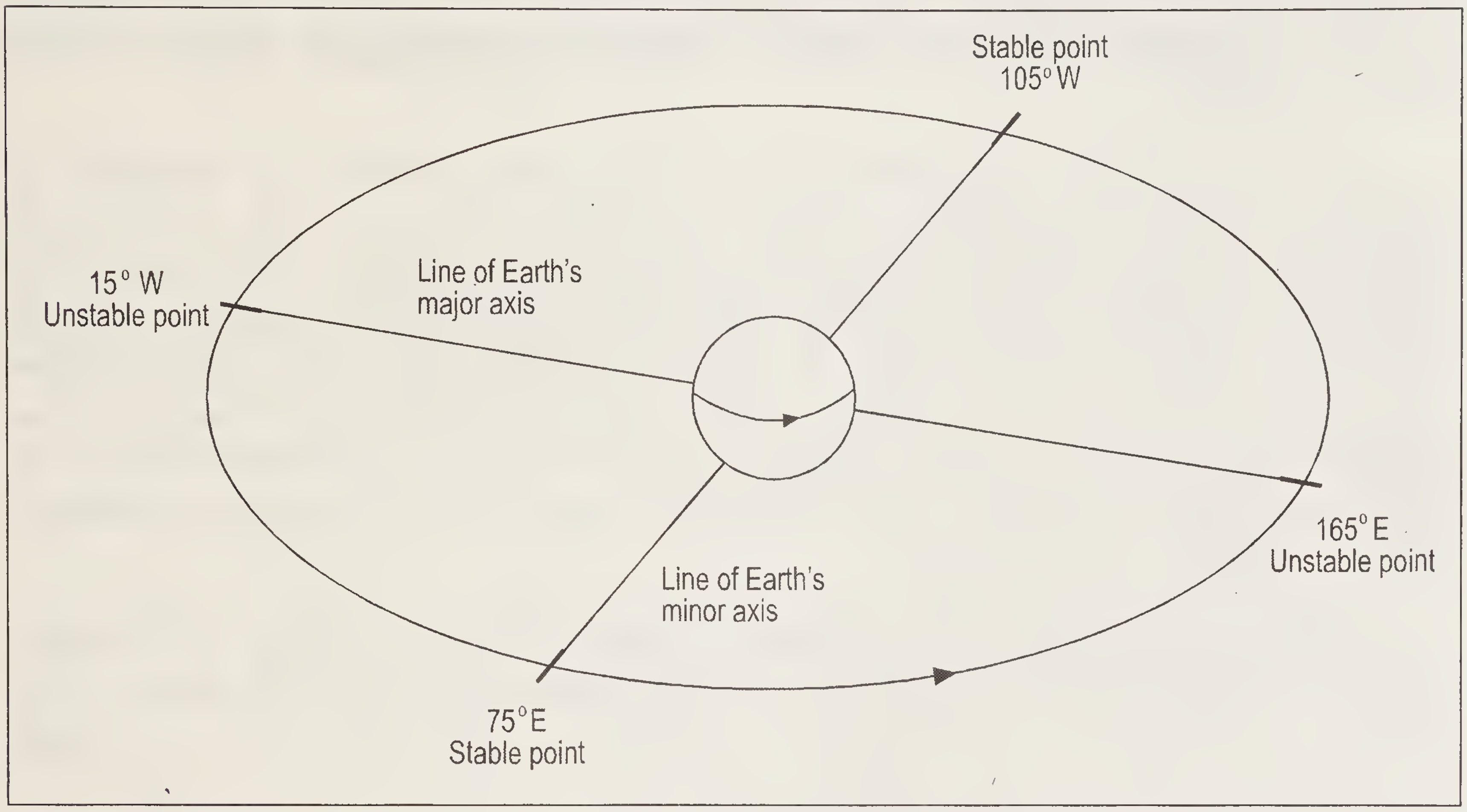


Fig 7.7 : A satellite in the geosynchronous orbit tends to drift, except at two stable points. The drift is controlled from the ground through radio commands.

allowed to drift at a rate of 0.5° per day towards its allotted position at 74 ° East longitude to be colocated on October 2 (2004) with Kalpana and INSAT-3C.. The satellite was raised again to GSO height when it reached the final location of 74°E on the 18th of October, where its payload was tested for ten days. It was eventually parked in between Kalpana-1 and INSAT-3C, which again was a delicate operation. The calculations and the duration of the thruster firings were perfect.

At any time the controllers would know the location of the satellite within five km. This is fantastic accuracy, given the vastness of space. MCF has seven earth stations, each with two or three antennas to work with the satellites. The antennas have different diameters viz. 14m, 11m, and 7.5m.

Another outstanding feature of the MCF operations has been the decrease in the outage (when the satellite goes silent, for example during loss of lock of Earth) over the years, from 12 hours in the case of INSAT-1 to one to two hours in INSAT-2, and now to virtually very small duration. Also, MCF successfully manages the days when the onboard battery has to be used, as the satellites pass through the Earth's shadow twice a year for about 45 days centred on the equinox dates (March 21 and September 21), the longest eclipse duration

being 72 minutes. It is the critical period, when the satellite needs maximum attention around midnight(local time) from the controllers.

There is another advantage of MCF's location, as it has the widest range of radio visibility of the arc of the geosynchronous orbit from 0° East longitude to 150° E longitude. The radio visibility enables the controllers to test any satellite over the region.

It is necessary to determine the position of the satellites as accurately as possible, so that the minimum distance separating them and the stability are maintained without interfering with the neighbouring satellites. With one ground station the distance to the satellite and hence the satellite's position can be determined within about five km. It has been found that with another ground station, also designed to do ranging (which means measuring the distance to the satellite), the accuracy of the satellite's position can be remarkably improved. Hence an identical second control facility has been set up in Bhopal in Madhya Pradesh, 1000km from Hassan.

If the two Facilities do the ranging simultaneously on a satellite, the accuracy of the orbit determination improves to a fantastic degree viz. 150 metres. (yes, metres, not kilometres!). The increase in accuracy of this order will be needed, as co-locating three or more satellites at the same orbital slot becomes more and more essential in view of future demands.

The Bhopal MCF is initially slated to monitor and control two geostationary satellites. The number is expected to go up to six in the next few years The Facilities (at Hassan and Bhopal) will be able to monitor the health of all the satellites in orbit as viewed from India and command them. ISRO is expected to control 20 satellites by 2010. Hence the Bhopal facility would be quite useful. Both the facilities enjoy an excellent 'radio visibility' coverage from the Persian Gulf to Australia. The geographical advantage together with a low radio noise environment along the 150° of the geostationary arc would enable the Indian facilities efficiently control its geostationary satellites over the Asia-Pacific region.

The arc in the geosynchronous orbit above the Indian Ocean is crowded with satellites of many countries and organisations. The International Telecommunication Union (ITU) allots slots for parking the satellites. Those who are capable of maintaining more than one satellite in the same slot without causing interference, are allowed to do so. Accordingly, ISRO has co-located some of its satellites. For instance, INSAT-3C, -4CR, EDUSAT and Kalpana-1 are at 74°E longitude; while INSAT-2E, -3B and –4A are at 83°E. INSAT-3A and –4B are at 93.5°E. Only INSAT-3E is at 55°E and GSAT-2 at 48°E.

25. Keeping Pace with Innovations

As a spin-off from the space programme, more than 300 small, medium and large industries benefit from commercial orders for quality parts and components. This policy enables ISRO to concentrate on innovations.

Communication satellites are becoming more and more powerful. As against 12 transponders (which relay the signals) on board, the world trend is towards 54 or 60 transponders in a satellite in the Ku band (10.7 GHz to 18 GHz), which are capable of direct- to -home television transmission. The growth is driven by demand for various services. Satellite makers all over the world typically recover the cost in the first three to four years of the 15 or 20 years of the satellite's useful life.

ISRO too is keeping pace with the latest innovations. Today, an INSAT can carry 12 high-power Ku band transponders, along with 12 C-band transponders.

The Space Applications Centre, Ahmedabad, has designed and made all the transponders for the INSATs from its second generation series onwards. Only the travelling wave tubes (output power amplifiers) alone have been purchased from foreign vendors. Even the antennas, which are the most expensive component, are made indigenously. Some of the transponder fabrication is carried out by BEL.

The power needs of the satellite depend on the efficiency of the solar cells it carries. Their efficiency has steadily improved from 11 percent with silicon cells, to 18 percent with gallium arsenide and 27 percent with what is known as triple junction solar cells. In another few years, multiple junction cells will improve the efficiency to 35 percent.

Improved solar cells would mean smaller solar panels and cheaper per watt power. Another contributory factor is onboard batteries that are needed during the eclipse time encountered by a satellite in the geosynchronous orbit twice every year. Nowadays batteries use lithium ion, instead of nickel cadmium, for improved efficiency and less volume. Yet another factor is the use of lighter materials in the fabrication of the satellite. Instead of aluminium honeycomb for the structure, carbon composites are used, as the latter give less weight-to-volume ratio. The electronic components are also getting smaller and smaller. Even in the RF

circuits, technologies like low temperature, co-fired ceramic substrate circuits are evolving.

The reduction in the weight of the structure should facilitate loading of more propellants for control of the satellite and thereby extend its useful life. INSAT-4 series, for example, is already designed to function for 15 years, which can easily extend to 20 years, if corrections to ensure the stability of the satellite do not gobble up the onboard propellants too early.

Some of the latest technologies are used in GSAT-4, the latest technology demonstration satellite. One is called onboard processing. Currently, the transponders act like a bent pipe and merely relay the signals sent from the ground. With onboard processing of the signals, it would be possible, for example, to distribute the power optimally to the coverage area. The beams can be adjusted to meet the variations in the demand for services. This calls for efficient coding of the instructions and other related techniques.

GSAT-4 will also deploy Ka band (multiple beam) transponders for the first time, as even the Ku band now being used may become crowded in another five or ten years. An advantage of Ka band is its larger bandwidth, though the band is more prone to rain attenuation. The beam in Ka band will have many narrow coverage areas, rather than one national beam.

Remote Sensing Techniques

Another area where technology improvements are taking place relates to remote sensing satellites in the near-Earth orbits. The spatial resolution of such satellites in detecting the status of ground resources has improved considerably from one kilometer to one metre. Cartosat-2 has one-metre resolution. ISRO's goal is to achieve a resolution of 0.5m to 0.25m, which would be on par with the best of some of the foreign satellites.

The resolution depends on the optics: the larger the aperture of the mirror, the better would be the resolution. For example, an aperture of 700mm at a height of 600km would yield a resolution of one metre on the ground. It would, of course, be necessary to reduce the weight of the mirror in such a configuration. Silicon carbide can be useful here, as it can stand the shaving off of 65 percent of its mass and still be strong enough for polishing. ISRO has funded research in this area, based on silicon carbide.

The other improvement of remote sensing satellites envisages the use of what is known as hyper spectral bands. The electromagnetic spectrum is divided into various narrow bands for remote sensing suitable for unique detectors. For example, the visible range {0.4 — 0.7 micrometre—(mm)} is divided into various spectral ranges: 0.45 – 0.52 mm (blue); 0.52 to 0.59 mm (green); 0.62—

0.68 mm (red) and the near infrared band at 0.77—0.86 mm; short wave infrared at 1.55—1.7 m. Dividing each of these ranges further would result in hyper spectral bands that would provide finer resolutions revealing the nature of the objects viewed or studied (including the presence of minerals etc). One can go up to 200 to 300 hyper spectral bands for various applications. To start with, ISRO is carrying a payload of 20 spectral bands in its moon mission, Chandrayaan 1.

One of the limitations of remote sensing satellites is clouds. Only microwaves emitted or reflected can be independent of the weather or daylight. It would therefore be essential to have a radar satellite, especially to acquire images during the monsoons. At present India mostly gets the radar images from Canada's RADARSAT-1. The Indian RISAT is getting ready. It would have synthetic aperture radar, which is state-of-the-art radar that would provide the benefit of a longer aperture and better resolution, without an aperture that is physically equivalent in length (see chapter 34).

As much as 50 percent of the total cost of the satellite goes to prove its reliability in space. Typically in a communication satellite, one aims at 75 percent reliability for service. Virtually every part is tested and evaluated for its space worthiness, though some cannot be tested on the ground. And in some low- budget missions like small satellites, it is not worth spending unduly large sums on ensuring reliability. This of course does not apply to launchers, where 100 percent reliability is required.

Unlike radar, which provides its own illumination, a microwave radiometer is a passive device, which would record the radiation from the ground and the atmosphere. The latter is also useful, especially in studying rain rate and atmosphere.

Extended C-Band

The increasing demand for telecommunication links requires an adequate number of frequencies for transmitting the signals. The traditional C-band is shared by terrestrial microwave links. Expansion of the C-band, though known to be technically feasible, required international agreement. India pioneered the move for the introduction of the extended C-band with a view to getting additional capacity. The International Telecommunication Union's wing for approving new frequencies, the World Administrative Radio Conference (WARC-1979), allowed the use of extended C-band and gave its specifications (6425-7025 MHz for the uplink and 4200-4500 MHz for the downlink). Its use does not involve coordination with terrestrial links as the latter do not utilise it. Following the approval of the extended C-band, the Indian Meteorological Department and Doordarshan agreed to use it. With ISRO's assistance, the equipment for its use was developed and made indigenously. The transmission of INSAT's meteorological data and Doordarshan's regional programmes was successfully put on the new band.

However, only after foreign collaboration was allowed, did the use of the new band pick up. For example, a VSAT network for the National Stock Exchange was set up in collaboration with a US firm.

The private sector developed indigenous hardware to use the extended C-band. A notable example is the talk-back terminal that is used for providing interactive training in teaching programmes on TV. In fact, the facility has opened up a new area for satellite TV, sometimes called narrowcasting, to indicate a restricted target audience for training and teaching specific groups.

26. Space Debris and Equity

Ever since the Space Age began on 4, October, 1957, space-faring nations have carried out more than 4,000 launches. They have resulted in over 26,000 objects in space. Two-thirds of them have burnt up on entering the Earth's atmosphere. Still there are about 9000 objects floating around as of January 2005. Only 6 percent of them are functional spacecraft. The rest is debris.

The objects that are tracked are more than 10cm in size in the low Earth orbit of 600—1000km above the Earth, where the remote sensing satellites usually are in orbit. Those tracked in the geosynchronous orbit at 36000km above the equator, where communication and meteorological satellites like INSATs are placed, typically measure one meter. In addition, it is estimated that there are fragments numbering anywhere between 100 000 and 150 000 varying in size from 1 to 3cm. Bolts, rocket parts and even specks of paint are going around, since they are not heavy enough to be pulled down by the Earth's gravity. Should any of the heavier objects fall into the atmosphere, due to say solar activity, they will burn up. The really heavy pieces will go through, as happened when the American Skylab and Russian Mir station reentered the atmosphere.

Almost one half of the debris has resulted from on-orbit explosions of rocket stages and non-functional satellites. The density of the debris is highest in the low Earth orbit and in the geosynchronous orbit. Though the probability of collision is calculated to be low, the problem will worsen, if no mitigation measure is taken in time.

Three aspects of the problem strike impartial observers. One, it is clear that Russia and the United States have contributed most of the debris, as they have launched most of the space rockets and satellites in defence and civilian areas. Second, only the United States and to some extent Russia have the capacity today to track the debris through optical and radar systems.

Third, it is possible to prevent the accumulation of debris in the geosynchronous orbit, if only the satellite owners are prepared to forgo some revenue and agree to re-orbit the satellite to a higher orbit at the end of the satellite's lifetime.

A solution is possible in the geosynchronous orbit. As a satellite there nears the end of its useful life, it can be kicked up to a higher orbit raised by 300km. But there is a catch. Raising the satellite at that height (36,000 km) needs an increase in the velocity of 11m a second, which in turn would demand the use of the propellant that may be used over three months for maintaining the satellite's stability. It would imply a loss of revenue (to a tune of Rs 10-30 crores depending on the satellite capacity) as the use of the satellite would end three months earlier.

The other mitigating measure is to drain all the propellant that remains in a stage after its use in orbit so as to prevent its explosion. It is also necessary to do complex calculations to ascertain the possibility of close approach of satellites or debris when a rocket is launched.

India has followed a policy of minimising the debris from the operation of its space missions. ISRO has developed software to predict the close approximation of any debris to functional satellites. For example, ISRO modified its launch of its PSLV-C4 by a few minutes as it was found that a piece of the previous rocket, PSLV-C3, might pose a collision problem. A part of PSLV-C3 (2001) broke up in space after its use into 330 pieces.

ISRO carries out a policy to remove all stored energy in the form of Earth storable liquid propellants and the cryogenic fuel from its GSLV upper stage after their useful working. ISRO emptied all fuel from the last stage of PSLV-C4 (2002) and verified its success from the pressure measurements. The last stages of India's launch vehicles PSLV and GSLV are so designed that the propellants remaining after the satellite is separated, are released

In the case of geosynchronous satellites, ISRO has decided to re-orbit the INSATs and GSATs to a higher orbit after the useful life of the satellites. The higher orbit (ideally 300km above the GSO) is called the graveyard orbit! This would help clear the GSO of unwanted satellites, as it has become crowded. ISRO successfully re-orbited INSAT-2C. ISRO raised the apogee of the orbit by 150km and emptied the spacecraft, despite the problems of visibility and propulsion constraints, meeting the international standards for such a measure to a large extent. Moreover, the software developed by ISRO was useful in predicting the time of re-entry into the atmosphere of the third stage of GSLV-D1 so as to avoid any future explosion of the spent stage. ISRO has developed the capabilities to assess the encounter with debris and the operations needed to re-orbit satellites.

As a developing country using space technology, India has stood up for equity and fairness in dealing with the problem of space debris at the international level.

Space debris has been essentially contributed by the early space-faring nations, proportional to the level of their space activities. Second, outer space

environment should be preserved for developing countries and new entrants without any constraints. Third, mitigation measures should be governed by guidelines. The adherence to them should be voluntary. Fourth, the data base on debris should be officially made accessible to the members of the UN Committee on Peaceful Uses of Outer Space. And finally, India favours what is called "common but differentiated responsibility" which in simple English means those who are largely responsible for the current debris and the capability to mitigate it should take the lead role in addressing the problem. India strongly opposes the idea of limiting any legal discussions only to the agenda of generation of new debris. Those who have polluted should not go without paying for it in some way.

Five U.N. treaties on Outer Space, adopted by the UN General Assembly, have some bearing on the problem of space debris, but so far there is no treaty on the subject of space debris itself. Accordingly, outer space is treated as the province of the whole humankind, not subject to national jurisdiction. Other agreed principal points include free access to outer space for all countries, prohibition of nuclear weapons in the Earth orbit and absolute liability of the launching state to pay compensation in the case of damage caused by space objects. It is also suggested by some experts that if the ownership of any specific debris cannot be established, damages to the victim could be paid from a "compensation fund" to which contributions could be in proportion to the launches since 1957.

But law alone cannot solve the problem of space debris. Technology plays a key role. And here the international power balance determines the approach. As India has the capability and the will to implement what it advocates, it has acquired a moral stature in espousing the cause of the developing world in matters relating to outer space.

PART - VIII

SERVICES FROM INSATs

27. A Preview of the Benefits

Telecommunications is one of the first applications of space technology. Beginning with a passive relay of voice and video signals by a satellite, active repeaters in synchronous orbit offered 24-hour service in telecommunications from 1965. Rapid advances in micro-electronics, satellite attitude control and deployable solar panels, paved the way for transition from international to national or domestic application of the technology. As satellites became more and more sophisticated, simpler ground stations were found adequate to handle the signals. In addition to underground cable and terrestrial microwave systems, satellites offered a third medium of telecommunication, with its advantages of diversity in a national network. The cost of connecting any place became independent of distance in a satellite system. Service over difficult terrain or water became possible and the time involved in laying ground links could be saved. The system was not affected by the weather. Maintenance became hardly a problem. Above all, transportable Earth stations became a reality.

Early Bird and Early Efforts

India became interested in adopting satellite technology for telecommunications even as the new technology was emerging. India joined INTELSAT (International Telecommunications Satellite Organization) in 1965, a year after its formation. INTELSAT operates satellites which can be utilised by its members for their international (and sometimes national) telecommunications. INTELSAT launched the world's first commercial satellite, Early Bird, in 1965. By then, a project took shape under the guidance of Dr. Sarabhai to establish an Experimental Satellite Communications Earth Station (ESCES) in Ahmedabad.

With assistance from the UN Development Programme and the International Telecommunications Union (ITU), an Earth station with a 14-metre fully steerable antenna was set up in a record time of 87 days. The station became operational in June 1967. To start with, a small team of engineers tried to work with ATS-2 spacecraft. But it did not achieve its designed orbit. Still, some video signals were sent to a laboratory in Japan successfully.

The Government set up a policy committee and a technical committee for drawing plans for space communications and to formulate a project for an Earth station to work with INTELSAT. Soon, work began on the country's first ground station at Arvi near Pune. The know-how developed by ESCES was quite useful in designing the project, which was entrusted to the Department of Atomic Energy in 1968.

Indian engineers made and installed a sophisticated Earth station in Arvi. The place was chosen because it was free from electrical and microwave disturbances. A prominent feature of the station is its 29.7m diameter antenna which was linked to INTELSAT stationed above the equator at 61.4°E longitude. Arvi could contact any INTELSAT Earth station from Japan to UK. The antenna can be kept pointed very accurately at the satellite, 36,000 km away. The station receives only an infinitesimal fraction of a watt in power and raises its level without increasing electrical noise. On the uplink side, the station has a high-power amplifier to supply the power required to radiate the signal-bearing microwave to the satellite. The uplink is operated at 6 GHz and the downlink at 4 GHz frequency, the exact parameters of which are specified for each ground station. The Arvi station (later named after Vikram Sarabhai) is linked to Mumbai by three repeater stations on hill tops in the Western Ghats with antennas facing each other, operating on a microwave frequency on a 130km route.

Arvi became operational early in 1971, with a test call to the U.K., through an INTELSAT satellite, followed by a telephone circuit established with Australia. India's overseas telecommunication traffic picked up in no time and within five years, the need for another Earth station was felt. It was set up near Dehra Dun, linked to New Delhi.

The First Experiment

The Arvi Earth Station was built, exceeding the specifications prescribed by INTELSAT.

This was followed by one of the largest experiments in satellite communication ever implemented viz., the Satellite Instructional Television Experiment (SITE). Several ground equipment such as direct reception sets, studio and low power transmitters besides transmit and receive chains were developed and made indigenously. The one-year SITE project was implemented in 1975 using the US ATS-6 satellite.

ATS-6 was the first communication satellite with three-axis body stability that enabled it to focus its beam accurately. It was called an umbrella satellite as it had a nine-metre diameter antenna. It was designed to provide direct telecast to about 2400 community receiving sets in as many villages in clusters of 400

each in six states, Andhra Pradesh, Karnataka, Orissa, Madhya Pradesh, Rajasthan and Bihar.

The emphasis of the programme was on rural areas. When SITE started, only five cities in India had TV stations, each of which had a range of 8 km! For the reception in rural areas, direct reception TV sets were developed by ISRO (its Satellite Applications Centre in Ahmedabad). A 3-metre antenna and a front-end converter for processing the signals were developed. The sets had five modules for easy replacement.

The main ground station for SITE was in Ahmedabad. In addition to the uplink to ATS-6, the station used its ground transmitters to send programmes to a nearby station in Bhuj through microwaves for rebroadcast to conventional TV sets. Almost all the villages had electricity. Every direct reception set's antenna had a unique look angle. Special arrangements were made for fault reporting and repair. Every day, 2 out of 100 sets failed, but within two or three days, it was repaired. Six areas involving four languages were covered. Two audio channels were broadcast simultaneously to go with one video channel.

Creating programmes suitable for different educational and social levels continues to be a big challenge. Surveys showed interesting details. The villagers liked informative programmes. School attendance improved. More women witnessed the programme. Illiteracy was not found to be barrier in gaining new knowledge. Still social customs discouraged women and backward sections from participating in the programme in full measure.

As the power of the satellite increased in the subsequent series of INTELSAT missions, small Earth stations became feasible and economical. In 1976 INTELSAT allowed the use of 10-m dish antennas with limited steerability for domestic service, while Standard A Stations such as those in Arvi and Dehra Dun were reserved for international telecommunications. The smaller ground station antennas were used in areas of moderate traffic or to provide domestic links.

In view of the advantages of smaller Earth stations, India decided to build seven of them mainly to connect Delhi and Chennai with remote areas in the country. The remote stations are Leh, Aizawl, Lakshadweep, Port Blair and Car Nicobar, which were commissioned progressively after March 1979. They were to form part of an eventual domestic network for telecommunication.

A Date with Symphonie

That year, a unique opportunity became available to Indian engineers to familiarise themselves with the advances made in domestic telecommunications. A Franco-West German Satellite, Symphonie, was loaned to India for two years from the middle of 1977 for conducting experiments under a joint project of ISRO

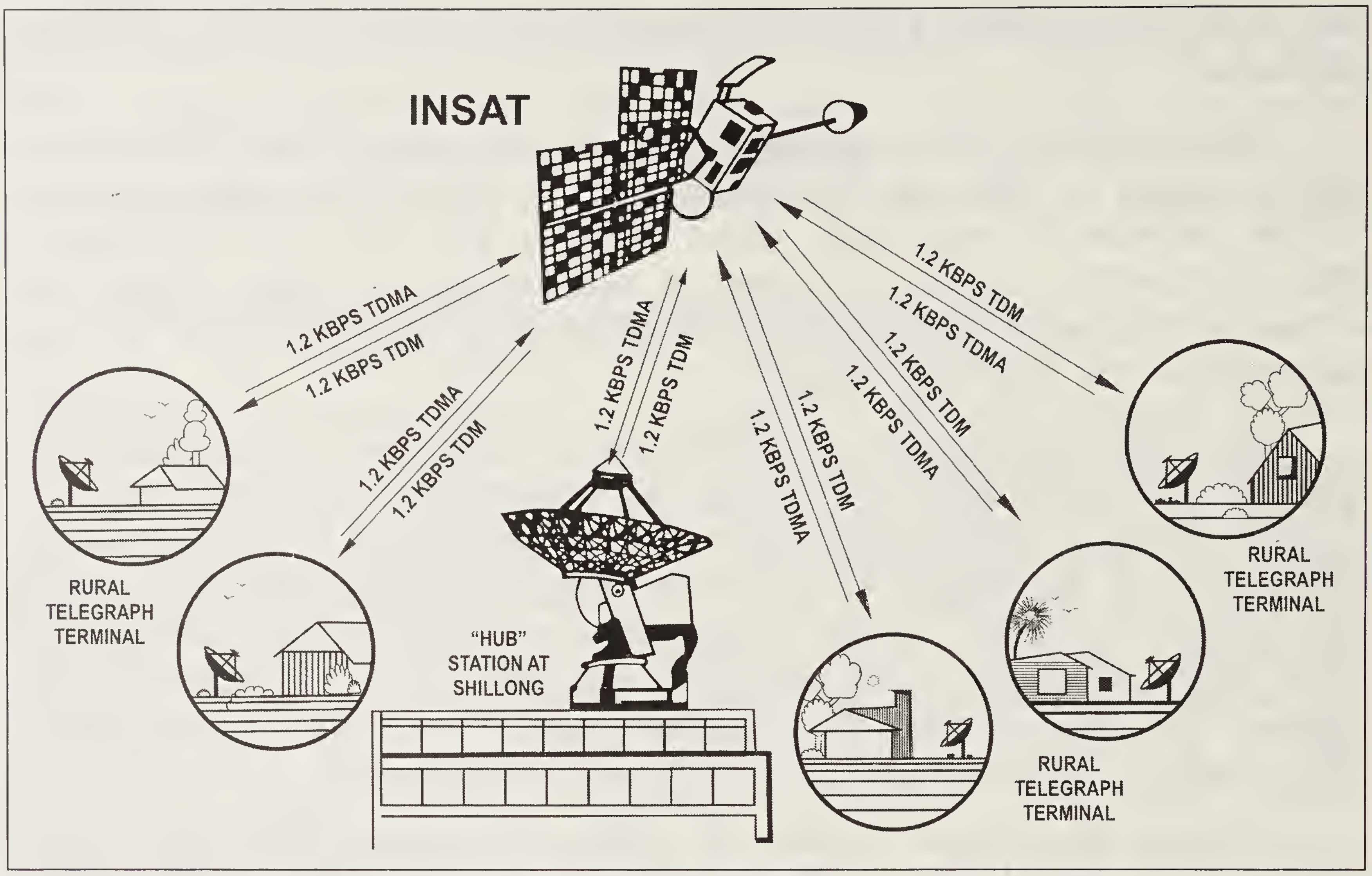


Fig 8.1 : A satellite-based Rural Telegraphy Network pilot project is implemented in the North-Eastern region.

and (former) P&T Department. The objectives were to provide a system test of a synchronous satellite for domestic telecommunications and to enhance the country's capability in the design, development and operation of various ground systems required for it.

Several experiments were conducted. Communication was established from remote areas through mobile transmitters. Advanced techniques such as digital communication and multiple access were tried.

28. Direct-to-Home TV and Other Services

The INSAT television system has been adapting to the changing demands of the country. Community viewing is no longer the preferred mode. Individual TV sets in households have increased. There has been an explosive growth in low-power TV transmitters fed by receive-only TV stations. TV channels for direct-to-home service have become popular. In the S-band of transmission, numerous services are operated, instead of community TV. And there has been a rapid expansion of regional TV networking in different languages. Digital data networks have increased the use of very small aperture terminals (Fig 8.2).

A total of 40 TV channels of Doordarshan and 47 private channels are operating through INSATs. Four transportable uplink terminals have also been provided.

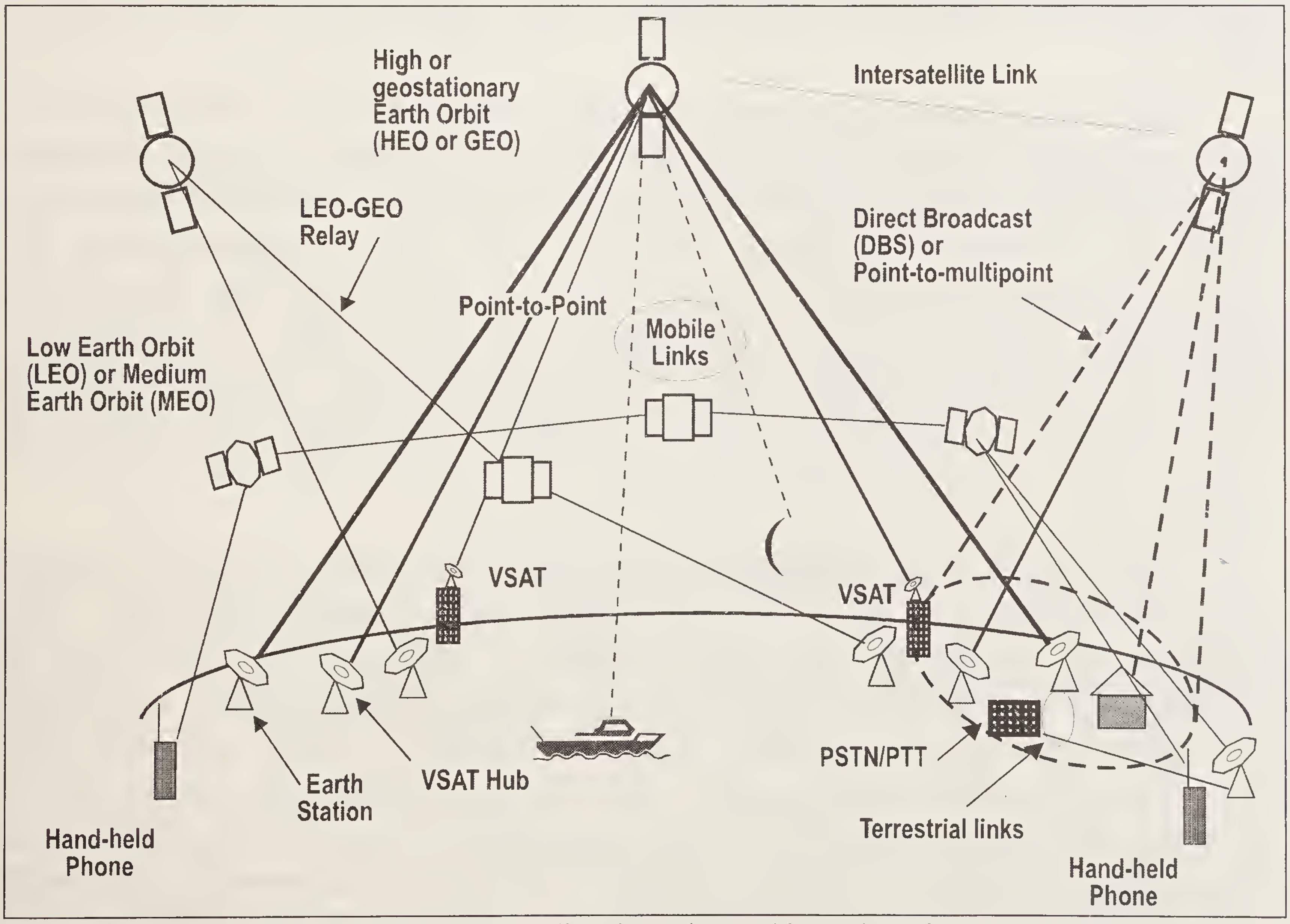


Fig 8.2 : Communication links between satellites in various orbits and small earth stations and handheld phones. Satellites also provide direct broadcasts to homes as well as point-to-multipoint links.

INSAT-4A and -4B are the most advanced Indian communication satellites, especially designed for direct-to-home TV (DTH TV). Several innovations have made DTH possible and useful.

There are different ways in which a TV signal can be transmitted. In the terrestrial mode, signals are received from a TV transmitter, which in turn is linked to a satellite. The range is limited to say 60km around a TV tower. There are over 1,390 TV transmitters in India connected to the INSAT system. The service is free. Cable television on the other hand is provided by private operators, who receive the satellite signals with their small ground stations and transmit them via cables connected to homes (wherever cables can be laid) on their terms and in return for periodic payments. DTH dispenses with cable operators, but needs a one-time investment (relatively inexpensive) on a small dish antenna and a decoder to connect the home TV. And there would be no more payments. It can also be connected to a TV set, in addition to its present link, if any, via the antenna pointed towards the terrestrial TV tower.

DD Direct, which started in December 2004 with two lakh customers, provides 33 TV channels, including many private channels, besides 12 radio channels free of subscription. Some of the private channels are not on the free-to-air system and those who wish to have them would therefore pay for cable TV.

There are about 100 million households that have TV in India today. Of them, some 40 to 50 million have cable TV, mostly in the urban areas. Doordarshan, based on INSAT domestic satellites, covers over 78 per cent of the land mass and 98 per cent of the population. (2003-04). Thus there is good scope for the reach of channels on DTH TV. In the next five years, more than five million customers are expected to have the service. But not all the TV channels are beamed from domestic satellites. There are 165 satellite-based TV channels beamed to the country and the INSATs carry 83 channels (51channels for Doordarshan and the rest for private channels), while the rest are transmitted by foreign satellites.

DTH TV has several advantages over cable TV. DTH TV can be received anywhere in India, as it does not need a cable link or ground transmitters. The equipment can be moved from place to place, if need be. For desert areas of Rajasthan, DTH is ideal, with solar- powered batteries, where needed. This would be a great advantage in providing additional channels to more and more rural areas. The picture and sound quality would be excellent and there would not be the hasslé of frequent breakdowns and withdrawal of service. A big increase in the number of channels is possible to cater to a variety of consumers. DTH mode can technically deliver more channels than can be done by cable TV.

The Digital Revolution

DTH has become possible because of some amazing technological innovations. First, there is what is known as digitisation of information. It simply means the technique of converting analogue signals (that continually vary according to the input) into on/off or 1 or 0 pulses in accordance with the input, suitable for handling by computers. The advantage of the digital mode is that all information, be it sound or vision or data, can be converted into electronic bits and recovered at the end point of transmission. This would not only save power but also eliminate unwanted noise in the transmission and would enhance the capacity of the transponder to handle more channels. A transponder – an electronic device – on the satellite that receives a signal, amplifies it, converts its frequency and rebroadcasts it back to Earth. The signals are transmitted in an abbreviated format and this is a big gain, as it would help conserve the limited bandwidth (the range of frequencies) allowed for the satellite by international convention. Compression is possible, as there is a lot of redundancy in video signals.

Technical compression of the signals enables engineers to transmit several channels into a single satellite transponder. In a digital mode, some 6 to 18 channels can be transmitted by one transponder, depending on the advanced electronics in it. For example, Sky TV proposes to provide 150 channels with 12 Ku transponders of INSAT-4A.

INSAT-4A and -4B provide what is known as Ku band transmission. The frequencies needed for this mode of reception of the signals from the satellite by small dish antennas are higher than those (C band) used for operating with the earth stations.

ISRO has had considerable experience in handling the Ku band from INSAT-2E in the 1990s, followed by INSAT-3B (2000), -3A and GSAT-2 (2003) and EDUSAT (2004). The operation of Ku band was perfected, even as thousands of VSATs were connected all over the country on C-band.

The Government of India allowed the use of Ku band for DTH only in March, 2001. The demand for DTH picked up quickly and the service was shifted from an INSAT to six Ku band transponders of a foreign satellite, NSS-6 of a Dutch firm. All the DD Direct TV and Zee TV's encrypted channels will continue to be carried by this satellite, even after INSAT-4A, which has been completely leased out to a private firm, Tata Sky Ltd, (Tata-Star DTH joint venture).

An interesting feature of DTH TV is the scope it offers to what is now known as narrowcasting. It means transmission of programmes meant for only designated groups of people and the signals are not for everybody. Even now it is possible but with smaller dishes and less complexity on the ground, the facility would be a boost for various types of training programmes in the country

for students, skilled workers and women. Moreover, DTH can make interactive television possible.

Radio Networking

All India Radio no longer relies on only terrestrial transmission. Radio networking through INSAT is now standard practice. Reliable, high-fidelity programme channels are broadcast for national as well as regional networking. Over 230 AIR stations have receive-only terminals and 84 stations can uplink programmes to the satellite. Many stations are being upgraded to ensure better reception.

AIR also provides radio channels along with the direct-to-home television facility.

The INSAT system provides satellite news gathering for real-time news coverage on the spot. Prasar Bharati has 12 terminals for the service for transmission to a central station at Delhi for rebroadcast over Doordarshan channels.

Press Trust of India provides through INSAT news and information services of higher speed directly to a wide range of media and other users.

Doordarshan's TV services include National Networking Service (DD-1), Metro Service (DD-2), Digital Satellite News Gathering Service and Regional Services of all the States of India.

The INSAT-based telecommunication services are provided with about 590 terminals of various sizes and capabilities. Over 10,000 two-way speech circuits or equivalent of about 490 routes are operated. In addition, the National Informatics Centre Network (NICNET) has over 800 micro-terminals. Several captive satellite networks are also operated by various agencies and government undertakings. There are about 198 VSAT's operating under the Remote Area Business Management Network. High-speed VSAT Network terminals for data and voice are also offered on lease. Both the government and private network operate more than 55,000 VSATs (Very Small Aperture Terminals) across the country.

INSAT transponders are also used to meet various societal and humanitarian needs such as education, medical aid, health and search and rescue. Interactive training programmes for various groups including women and panchayat leaders are also implemented. INSAT forms part of the International Cospar-Sarsat System, providing geosynchronous orbit coverage for the Indian Ocean Region, the only one of its kind in the Region (Fig 8.3).

The INSAT system, dedicated to the nation in 1984, completed 23 years of service in 2007. It is expected that the satellite-based communication would continue to grow at 40 per cent per annum. The areas that would need satellite-based services are: broadband services that connect the Internet and video

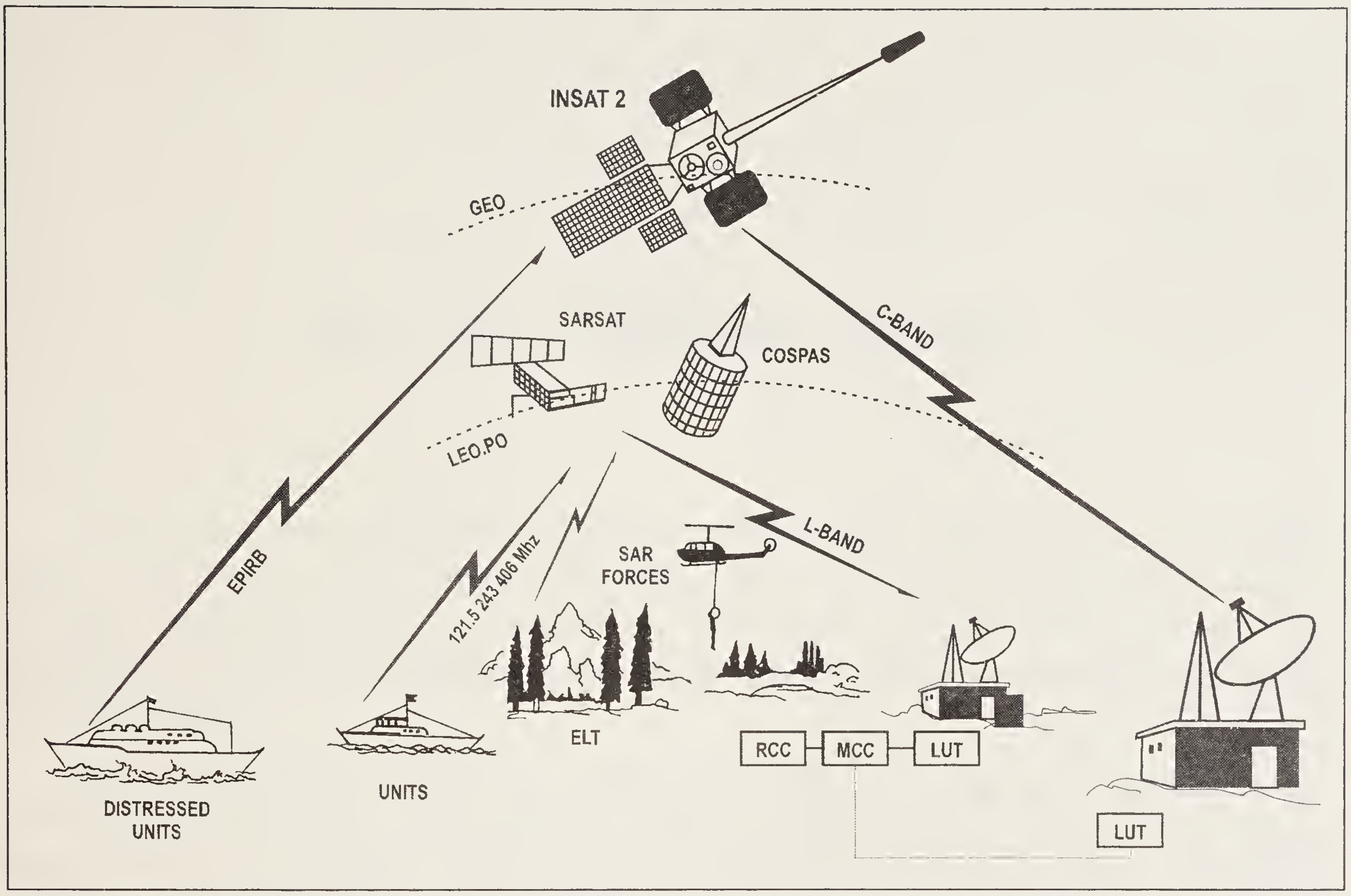


Fig 8.3 : Satellite-aided search and rescue: INSAT can detect in almost real time a distress signal and send out signals to the Master Control Facility in Hassan. The signals are then fed to COSPAS -SARSAT Mission Control in Bangalore for relay through low-Earth orbiting satellites. India is the first developing country to incorporate the geostationary statellite component in search and rescue operations.

broadcasts; increased use of small-size VSATs in the Ku band; stand-by services for corporate and bank users; usage in the neighbouring countries, especially the SAARC countries, (with the availability of a wider 'footprint' area of coverage with sufficiently powerful signals); connection to Internet Satellite Gateway operators in India and abroad (who now work through foreign satellites).

The optimal use of the space segment demands efficient interference-free operations with proper co-ordination.

29. The Weather Watch

The term monsoon means seasonal rainfall. The word *mausam* in Arabic means season and Arab sailors and traders had used it to mark their voyages to India. Monsoons need a large land mass and a large ocean. They arise basically because of a temperature difference between the land and the sea, going up to 20 deg C.

The south-west monsoon in India from June to September accounts for more than 75 per cent of the annual rainfall in most of the country. The Indian Meteorological Department (IMD) predict rainfall over the country. The probability of a rainfall deficiency is also indicated.

Forecasting The Monsoon

Kalpana-1, India's exclusive metsat at 74 deg East longitude over the equator, has in its imagery of June 1, 2006 shown the initial pattern of the monsoon, as it hit the west coast. Observers have found that in the days prior to the onset of the monsoon, very strong winds were blowing in the upper atmosphere above the southern Arabian Sea. The easterly winds were coming from Somalia towards India. They were called the Somali jet, which is an essential part of the south-west monsoon circulation. This is also connected to the weather pattern over Siberia, where the air in summer is warmer than the surrounding seas and this feature contributes to the emergence of the winds over the Arabian sea. The Western Ghats in south India split the winds into two, one striking the coast near Mumbai and Mangalore and going towards Pakistan later and the other turned eastward over the warm Bay of Bengal towards the north-east, causing among things the famous copious rain on Cherrapunji (making it one of the wettest places on the Earth). The hills in route to Assam on the eastern side add to the moisture content of the winds. Some six weeks after they hit south India, the monsoon arrives in north-west India. In the winter, the air over Siberia becomes colder than the surrounding seas, which lead to cool north-east winds blowing across the Indian subcontinent. Currents called the *westerlies* in September mark the end of the south-west monsoon over north India (Fig 8.4).

Ever since the first weather satellite was launched in 1960, satellite data have been incorporated into weather forecasting. Weather data from space are obtained in three ways. First, satellite imagery of the cloud cover which we see daily on the TV can provide more than mere pictures: surface temperature, wind speed and direction and cloud height etc. can be calculated. Second, infrared and microwave sensors on satellites can 'sound' the atmosphere by passively recording its features. This way humidity and even ozone levels can be deduced. The third method is called active as the sensors on the satellite transmit energy and record the pattern of its backscatter to know the nature of the atmosphere. The data collected by satellites and monitoring platform on the sea and land are gathered, integrated and studied in what is called numerical weather forecasting. Powerful computers are necessary to process the data. This is still being perfected as a worldwide effort.

In India, the National Centre for Medium Range Weather Forecasing in Noida near Delhi is engaged in research and forecasting the weather. The Centre aims to provide farmers weather crop information within three to ten days. The Centre is acquiring a new computer, called Cray-XIE Super Computer for the purpose. It would make the Centre the most powerful system in the region for weather forecasting. Indigenous efforts are also being utilised. The National Aeronautical Laboratory in Bangalore has developed the country's first parallel computer and has come out with improved models.

It is worth recalling that it required nine years since the first weather satellite to introduce the first temperature profile obtained from a satellite into the numerical weather forecasting (NWF) model. In the 1970s and the 1980s, better estimates of moisture and wind velocity were included and in the 1990s satellite measurements of the Earth's radiance registered in narrow bands were added to the NWF.

Satellite data are one of the most important ingredients in weather forecasting techniques. Repetitive and synoptic weather system observations over the Indian Ocean from the geosynchronous orbit are available only from the INSAT system (INSAT-2E, –3A and Kalpana-1). The products include cloud motion, sea surface temperature, outgoing long-wave radiation, and precipitation pattern. In addition, INSAT-3D (to be launched in 2007-08) will be an advanced metsat carrying among others an imager and sounding instruments.

Recently two features of the sea have emerged as important inputs for weather forecasting: sea level temperature and sea level height. The latter can now be calculated within two centimetres! The European environment satellite, ENVISAT, for example, has found that the sea level height between the western and eastern Pacific differs by as much as 60 cm. Another finding by the climate

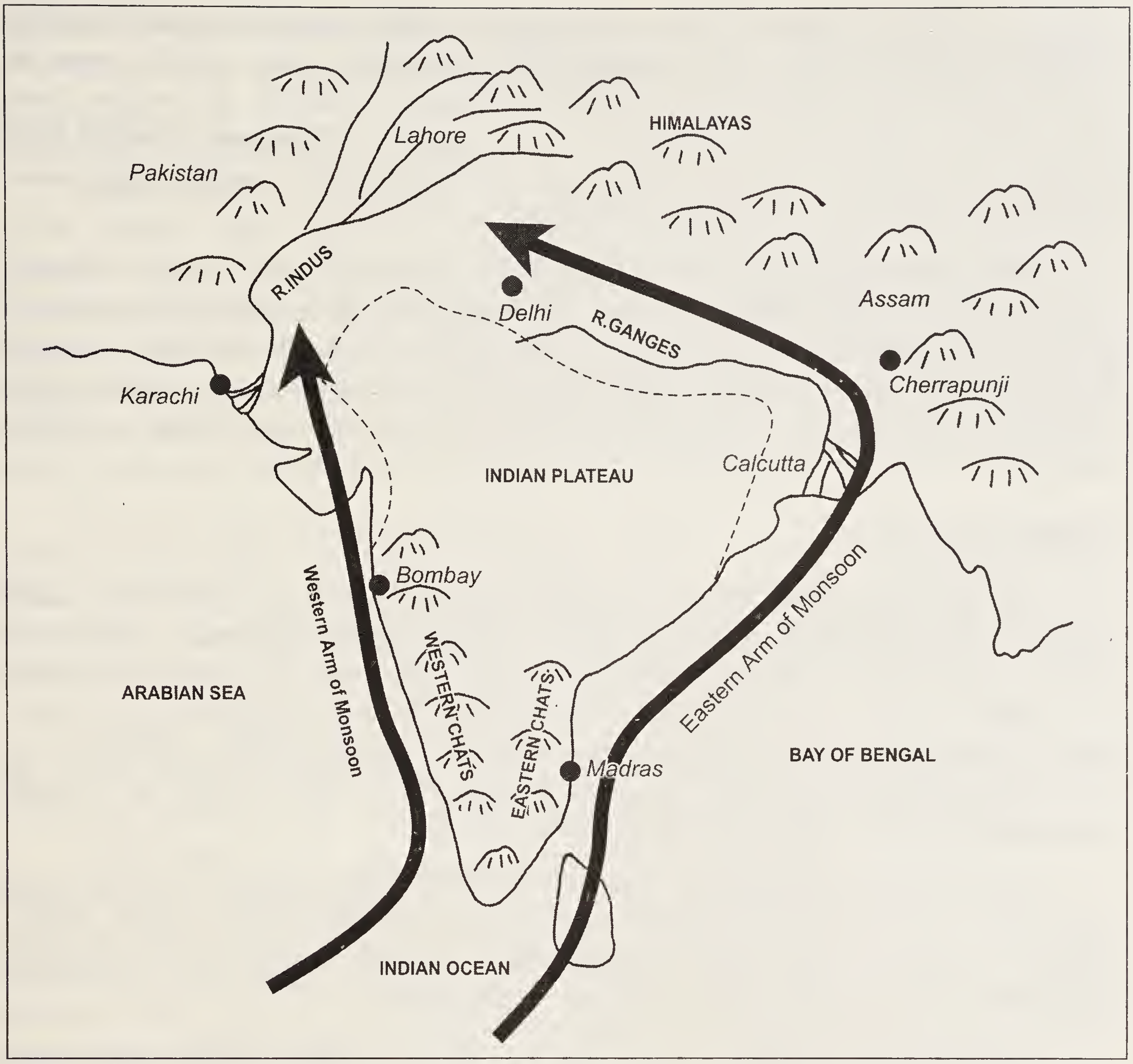


Fig 8.4 : Monsoon directions

experts is the steady rise in the sea level temperature, which carries the potential to intensify the tropical storms across the globe.

ISRO has an agreement with Europe's EUMETSAT on sharing the data from its METEOSAT-5 at 63^0 East longitude in exchange for INSAT data.

The first sounding rocket to probe the lower atmosphere from Thumba was launched in 1963 and a few weeks later, the first cloud picture was received in Mumbai from a satellite. The two events, though juxtaposed by chance, revealed a new world of study to the weather experts.

Several of the early rockets made in Thumba were used to carry meteorological payload. Rohini-100 and Rohini-125 were of this category. Slightly bigger rockets, RH-200, were later used regularly to launch payloads of up to six kg to a height of 60-90 km for the study of temperature, humidity and wind

velocity at different heights of the atmosphere. In 1970 a programme of launching Russian sounding rockets on a regular basis started the study of the upper air circulation from the Arctic to the Antarctic. Known as M-100, the rockets went up to 90 km and during the descent of the payload (which was delayed by a parachute that opened at 65 km), data were collected on the outside temperature, the state of the sea and other parameters.

India also participated in the MONEX-79 experiment, which was a monsoon expedition in the Indian Ocean. It was a sub-programme of the Global Atmospheric Research Programme (GARP) under the joint auspices of the World Meteorological Organisation and International Council of Scientific Unions. The expedition studied the factors underlying the onset and withdrawal of the monsoon. These and other programmes revealed several interesting features of the Indian monsoon.

Satellite Sensors

The first generation weather satellites operated by the United States used television cameras to take cloud pictures. Simple ground equipment installed in several countries including India was able to get the pictures in real time during the satellite's pass over them. It took about 30 minutes to record one picture. Later generation satellites were able to store and relay data. Then came the use of sensors which recorded data in infrared channels. It was possible to measure from satellites the temperature at different altitudes.

Geostationary satellites have constant field of vision and can therefore track the motion of clouds and indicate wind movements. Four or five geostationary satellites needed to cover all longitudes were provided under an international programme of the World Meteorological Organisation.

The enormous quantity of data put out by the weather satellites demanded high-speed computers to process them. Computers made it possible for the experts to build mathematical models of weather patterns and verify their validity.

Indian weather experts became familiar with the use of cloud pictures received from American satellites and the weather data collected by Russian Meteor satellites and transmitted to Delhi. Tracking of cyclones became possible.

A weather satellite can act as a data link receiving data from a variety of places and transmitting them to a ground station. Such a facility has for the first time made data collection from remote and difficult areas cost-effective and technically feasible. The need for supplementing satellite data with ground-based information collected from a wide range of places including the oceans emphasised the need for a domestic satellite system.

Indian scientists gained valuable experience in designing and operating a microwave radiometer aboard the country's first experimental Earth observation

satellite, Bhaskara. It was useful for deriving weather data such as atmospheric gradients, ocean surface winds and precipitation rates over the oceans.

The INSAT System

When INSAT was designed, considerable importance was given to the study of the weather. The system was designed to provide round-the-clock half-hourly, synoptic images of the weather conditions including cyclones, sea-surface and cloud-top temperatures, water bodies and snow over the entire country and the adjoining land and sea areas. In addition, it was designed to collect and transmit meteorological, hydrological and oceanographic data from unattended remote platforms. The system would provide timely warnings of cyclones, floods and storms.

The Very High Resolution Radiometer (VHRR) on the INSAT series provides weather information. The VHRR acquires visible (in 0.55-75 micrometres) and infrared (10.5-12.5 micrometres) images. They are analysed to derive spatial cloud maps, wind speed and direction at different heights in the atmosphere, sea surface temperature and estimates of precipitation (Fig 8.5).

INSAT-1 VHRR had a spatial resolution of 2.75 km in the visible band and 11 km in the infrared band. Its successor in INSAT-2, made in India, gives a better performance, viz. 2 km in the visible and 8 km in the infrared channels.

The VHRR is a sophisticated instrument. Radiation from the ground is reflected on to a 200 mm aperture telescope using a beryllium mirror. The scan mirror is mounted on a two-axis mechanism, which generates the image by sweeping the instantaneous field of view (IFOV) in the east-west and north-south directions. The optical system is a beam splitter that reflects infrared (IR) energy but transmits visible light.

In realising the VHRR, several subsystems were developed for the first time: its large telescope, the passive radiating cooler, a 2-axis scan mechanism axis and the related electronics.

INSAT-2 provides three imaging modes: a full frame mode covering 21.4° East-West (E-W) x 20° North-South (N-S) in 33 minutes; a normal mode covering 21.4° E-W x 14° N-S in 23 minutes and a sector mode that can be positioned anywhere in steps of 0.5° in the N-S direction to cover an area bound by 21.4° E-W x 4.5° N-S. The visible and IR detector data are individually processed and transmitted to the Indian Meteorological Department at New Delhi. A cloud cover picture is taken every three hours. More frequent images are generated, when necessary. The data are used in cyclone tracking and for prediction of storm surge, etc. The IR data are used for deriving sea surface temperature around India on an experimental measure. Weekly precipitation estimates and data on the

outgoing long wave radiation have been useful for predicting the weather for agricultural purposes.

The footprint of the data relay system covers the entire visible Earth disc. Unattended data collection platforms (DCPs) specially designed for INSAT can accept data from 15 instruments, digitize them, format, store and transmit them every hour on the hour to the satellite. The Space Applications Centre (SAC) was the lead centre for the INSAT-2 VHRR; the scan mirror mechanism was designed and fabricated by the ISRO Inertial Systems Unit; the mirror by the Laboratory for Electro-optical Systems; and the cooler by ISRO Satellite Centre. Several laboratories outside ISRO were also involved. The Indian Institute of Astrophysics, Bangalore, did the optical polishing.

A computer-aided VHRR evaluation system was developed at SAC and used for a comprehensive payload performance evaluation. Though the image cannot be seen during testing on the ground, on-orbit data showed that the specifications of the instruments were exceeded by 35 per cent.

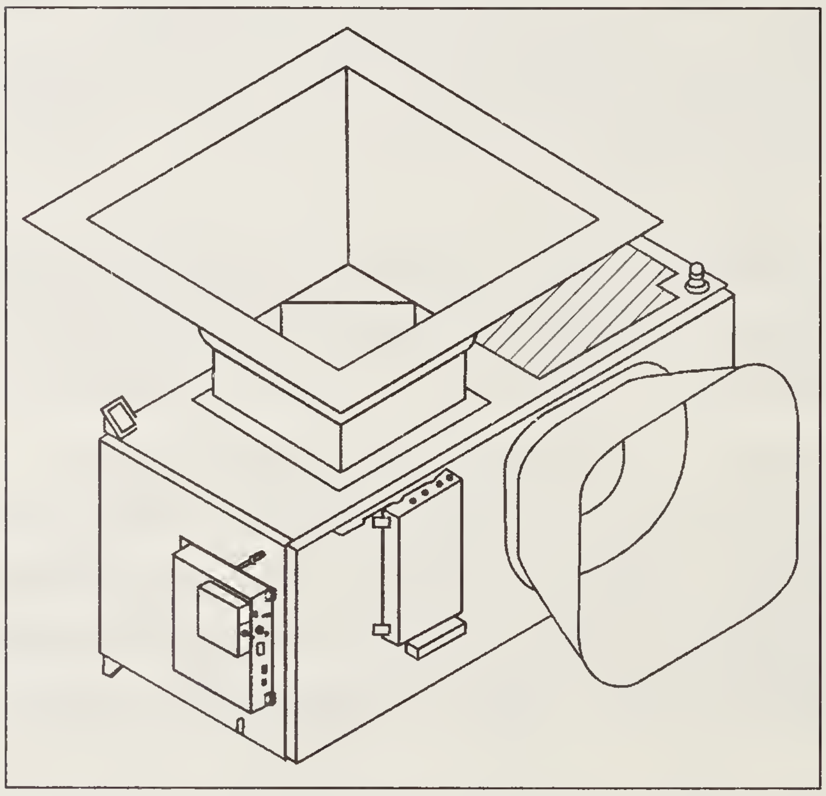


Fig 8.5 : The Very High Resolution Radiometer for INSAT -2, developed indigenously, has a resolution of 2 km in visible and 8 km in the infrared band.

INSAT-2E included for the first time a water vapour channel operating in the infrared region. The data on the moisture in the middle levels of the atmosphere are useful for forecasting tropical cyclone motion.

Kalpana-1, the country's exclusive geostationary weather satellite (launched in 2002), has also a water vapour band. Its visible band can resolve 2x24m with better optics.

Data relay transponders are in Kalpana-1 and INSAT-3A. The India Meteorological Department has installed 100 weather data collection platforms, and other agencies have set up about 200 such platforms all over the country. Specially designed receivers to get warnings of impending disaster from cyclones have been installed in vulnerable coastal areas of the country. One of them is at the Indian base station in Antarctica.

INSAT's VHRR data can be made available at any location in the country, through a direct satellite service. A rainfall monitoring system has also been developed.

Disaster Warning System

A disaster warning system is operated through INSAT. Disaster warnings (prepared by the cyclone warning centres) are broadcast directly and selectively to the areas likely to be hit by cyclones. Simple receivers are located in vulnerable areas along the country's east coast in Tamil Nadu, Andhra Pradesh, Orissa and West Bengal. The receivers are tuned to particular codes transmitted by the satellite and activate a loud siren for about a minute. This is followed by the cyclone warning centre (Fig 8.6).

A Decision Support Centre (with a 4.8 m antenna to handle satellite signals relating to emergency situations) has been installed at NRSA, Hyderabad linked to Central government agencies.

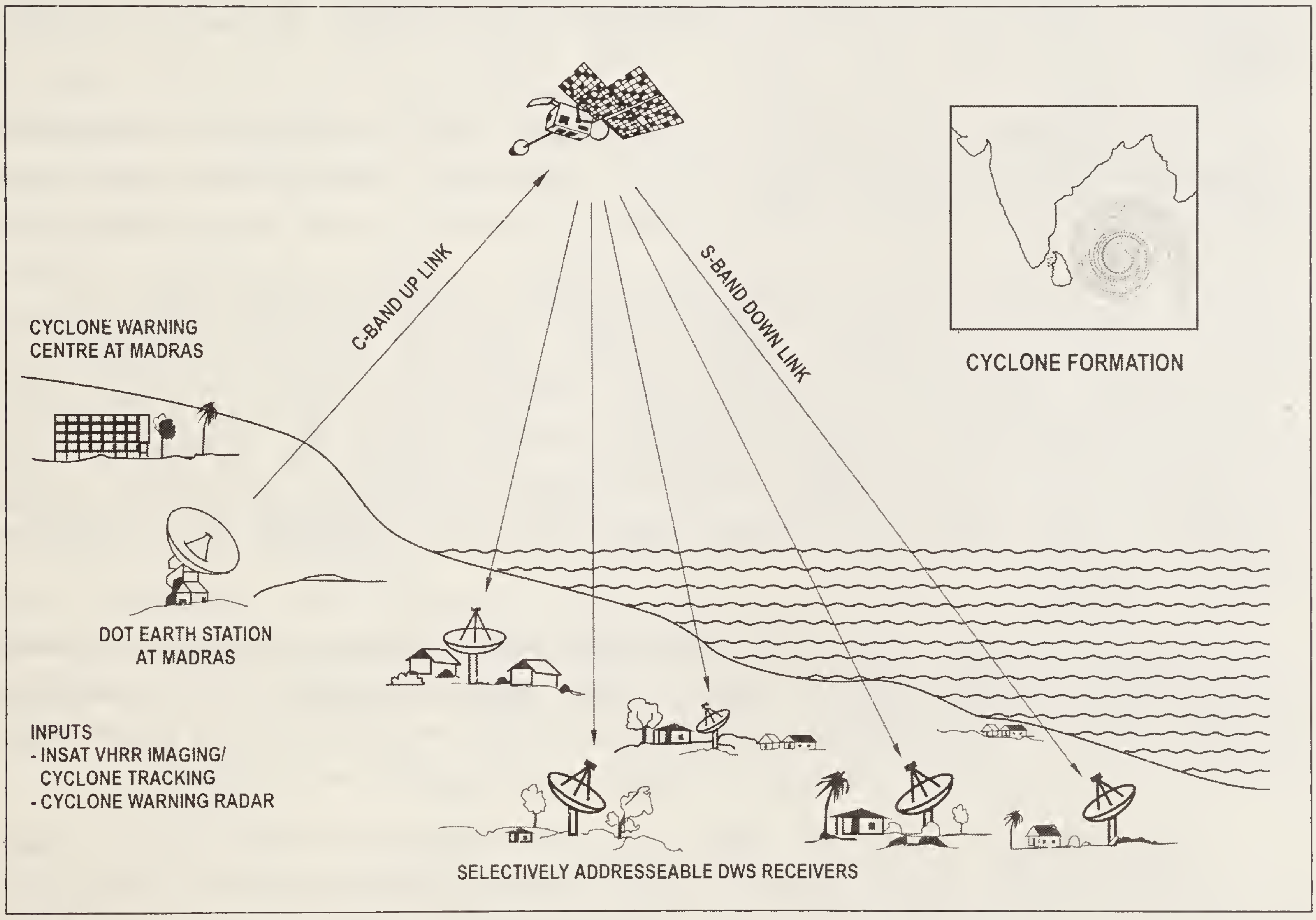


Fig 8.6 : Disaster Warning System: Cyclone warnings are provided in the local language, after selected receivers are activitated by a INSAT signal to sound a loud siren.

COSPAS-SARSAT

In 1987 India joined the COSPAS-SARSAT system. India is the first Asian country to incorporate the geostationary satellite component in a search and rescue system. Though satellites in lower Earth orbits can provide alert information, the frequency of their passes, particularly over the equatorial regions, is limited. Hence a geostationary satellite, which has a fairly high power, can detect a distress signal

in almost real time and initiate search and rescue in the quickest possible time. The first two of the INSAT-2 series had receivers on board to get distress signals from the 406 MHz beacons on the ground for rebroadcast. INSAT-3A has an identical payload. India has two local user terminals, one at Lucknow and the other at Bangalore, that cover a large part of the Indian Ocean region. The ground control is located at the INSAT Master Control Facility which in turn relays the alert to the COSPAS-SARSAT Mission Control Centre in Bangalore.

Predicting a Tsunami

Tsunami in Japanese means a harbour wave, though it arises far from any harbour. Nor can it be described as a tidal wave, though a tide may add to its speed. A tsunami is best described as a wave train, or a series of waves generated in water by an impulsive disturbance that vertically displaces the water column.

The prediction of a tsunami works like this: following an underwater earthquake, pressure sensors placed on the ocean bed pick up the signals and transmit them to the floating buoys on the sea, which in turn beam them up to a satellite for transmission to warning centres in Alaska and Hawaii, where computers model their threat. Though tsunamis are common in the Pacific Ocean, they are generally too small to cause concern. The size, speed and direction of a tsunami are determined by the contours of the seabed and local topography. The wave height of a tsunami depends on the seabed: the shallower it is, the higher is the wave height. Even a modest earthquake can cause a big tsunami! It takes about two to three hours after the earthquake for a tsunami to hit a coast.

It is now known that the International Tsunami Warning Center in Hawaii did send out warnings within 15 minutes of the 2004 earthquake to its 26 member countries (India is not a member) including Indonesia and Thailand. In South Asia, no tidal gauges or buoys for the detection of tsunamis are in place.

The earthquake occurred when, at a few kilometres below the sea bed, the continental plates slipped abruptly over a thousand kilometre stretch, giving rise to a 10 m high cliff and a tsunami, which gathered a speed of over 800 kmh, almost that of a jet plane.

An accurate knowledge of the seabed is essential to locate the place where the plates slip. The Earth is a rocky planet with a diameter of 12,756 km; but its core is only 6,900 km across. Surrounding the core is a mantle some 2,900 km thick. On the top of the mantle is a layer called lithosphere, which is 80 km thick and has moving plates that contain the continents and oceans. The Indian plate dips some 40 m into the mantle in the south.

India has decided to install imported pressure sensors on the ocean bed. The data have to be relayed to a satellite and it is likely that India's future weather and communications satellites will provide for data receive and relay transponders for tsunami warnings, in addition to those now floated for weather data relay. Satellite-borne radar altimetres in foreign satellites are used to measure the topography of the ocean surface. Changes in the sea level have to be detected to track a tsunami.

Though tsunami warning is still in its infancy, a fundamental solution to detecting one is likely to be found in space. Russian scientists had all along been claiming that earthquake precursors could be found in the ionosphere, which is the radio mirror in the sky, extending from 70 km to 1,000 km above the Earth's surface. However, the Russians could not in the cold war days reveal the source of their claim, viz. secret military satellite signals that were affected by the ionosphere. In fact, the Russian Intercosmos-19, followed by the American OGO-6, Nimbus, the French Aureol-2, GEOS-1 and –2 had reported earthquake-related space-borne phenomena a few hours or even days before the main shock of earthquakes.

It is now known that the largest seismic wave moving the ground during an earthquake called the Rayleigh wave, produces shock waves which in turn lead to disturbances in the ionosphere. One millimetre displacement of the wave (from its peak to peak) on the ground, it seems, will cause oscillations larger than 100 m at a height of 150 km in the ionosphere. In 2002, similar oscillations were recorded after an earthquake in the U.S. by six global positioning satellites (GPS). It is known that GPS signals are affected by the variations in electron density in the ionosphere. The ionosphere can thus offer a clue to seismic ground disturbances and the technique can further be improved to detect tsunamis that may follow a 7.6 scale earthquake after a gap of some two or three hours.

30. EDUSAT and Telemedicine: A Beginning

A satellite exclusively designed for education, EDUSAT, was a dream of Vikram Sarabhai. Great expectations about its role marked its launch in 2002. However, after five years of operation, the road less travelled in the field of education seems to throw up numerous roadblocks against full utilisation of the satellite. Many States have yet to plan its regular utilisation.

EDUSAT is no doubt a technological masterpiece. It is designed to provide multimedia lessons and augment distance education facilities in the most modern way. The satellite has a national beam and five spot beams to cover as many

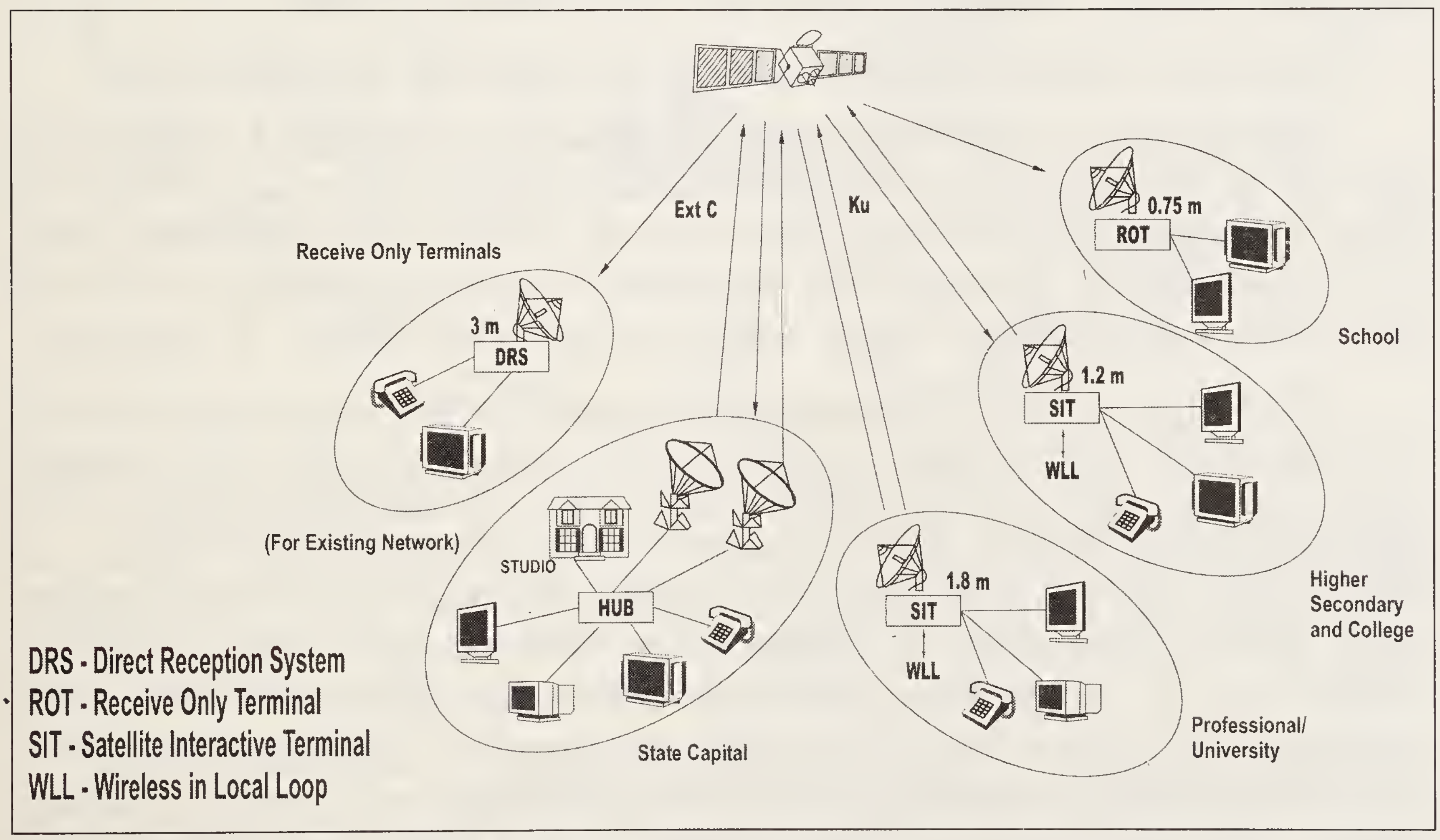


Fig 8.7 : EDUSAT's links at different levels of learning.

regions in the country, viz. the north, the north-eastern, the eastern, the western and the southern regions. The entire country can be covered by one high power Ku band and six C-band beams. Nine networks in the national beam and 22 in the regional beams are in use with over 10,000 terminals (2007). Two-way audio, one-way video, interactive TV, video and computer conferencing and web-based instructions are possible. Lessons are prepared and transmitted to the satellite for rebroadcast (Fig 8.7).

One of the early users of EDUSAT is the Visvesvarayya Technical University with its 121 affiliated colleges in Karnataka. The lessons in various branches of engineering are telecast daily. The first-ever interactive VSAT channel with two-way video and two-way audio has been introduced to the first batch of 30 selected colleges. VTU is the first university in India to have two satellite channels for training and education. Several other universities and national institutions also make use of the satellite: Indira Gandhi Open University, Rajiv Gandhi Technical University, Y.B. Chavan Open University pilot network, the National Council for Educational Research and Training, Department of Science and Technology, the Technical Education Board in Rajasthan, the West Bengal University of Technology (Kolkata) and Manipur University (Imphal).

Some primary schools in Karnataka have also received specially prepared lessons from the satellite. Institutions in some other States – Uttaranchal, Madhya Pradesh, Bihar, and Kerala are also planning to use the satellite. In Gujarat, ten blind schools make use of EDUSAT with the participation of the Blind People's Association. In all, some 2300 classrooms are connected (2006).

There are, however, no two opinions that EDUSAT is underutilised.

It has become a classic example to prove that there cannot be a technological quick fix to the deep-rooted problems in social sectors in the country. While the efforts of the institutions that have tried to use the satellite are commendable, there is an urgent need to do some basic homework to plug the loopholes if any and bring about radical changes where needed in the whole system of education.

There are some basic constraints on the ground which need to be remedied, if the space link were to make a difference. The syllabi of most of the courses, which form the basis of the satellite lessons, are outdated. The output is not qualitatively different from what is available in the traditional mode. The best of teaching talent has yet to be attracted with good remuneration and facilities. The timing of the lessons from the satellite is not well integrated with the teaching schedule and the satellite-based inputs are seen as an optional extra rather than an essential part of the course. The satellite has turned the spotlight on the quality of the education that is dished out, despite the proliferation of a variety of subjects offered. Ultimately, a course will be popular, if it is useful and relevant to the students, irrespective of the mode of delivery. The satellite should reduce rather than increase the burden on the students.

The target of serving the primary schools would succeed only if attendance and dropout rates are brought down by schemes like provision of midday meals. There is also a need to use the satellite for non-formal education and outside the usual school hours.

Telemedicine

Telemedicine through INSAT has become a reality (Fig 8.8). A pilot project in Karnataka began operation in 2002, connecting a district hospital with Narayana Hrudayalaya, a super-specialty hospital in Bangalore, led by Dr Devi Shetty, famous for carrying out thousands of open-heart surgeries.

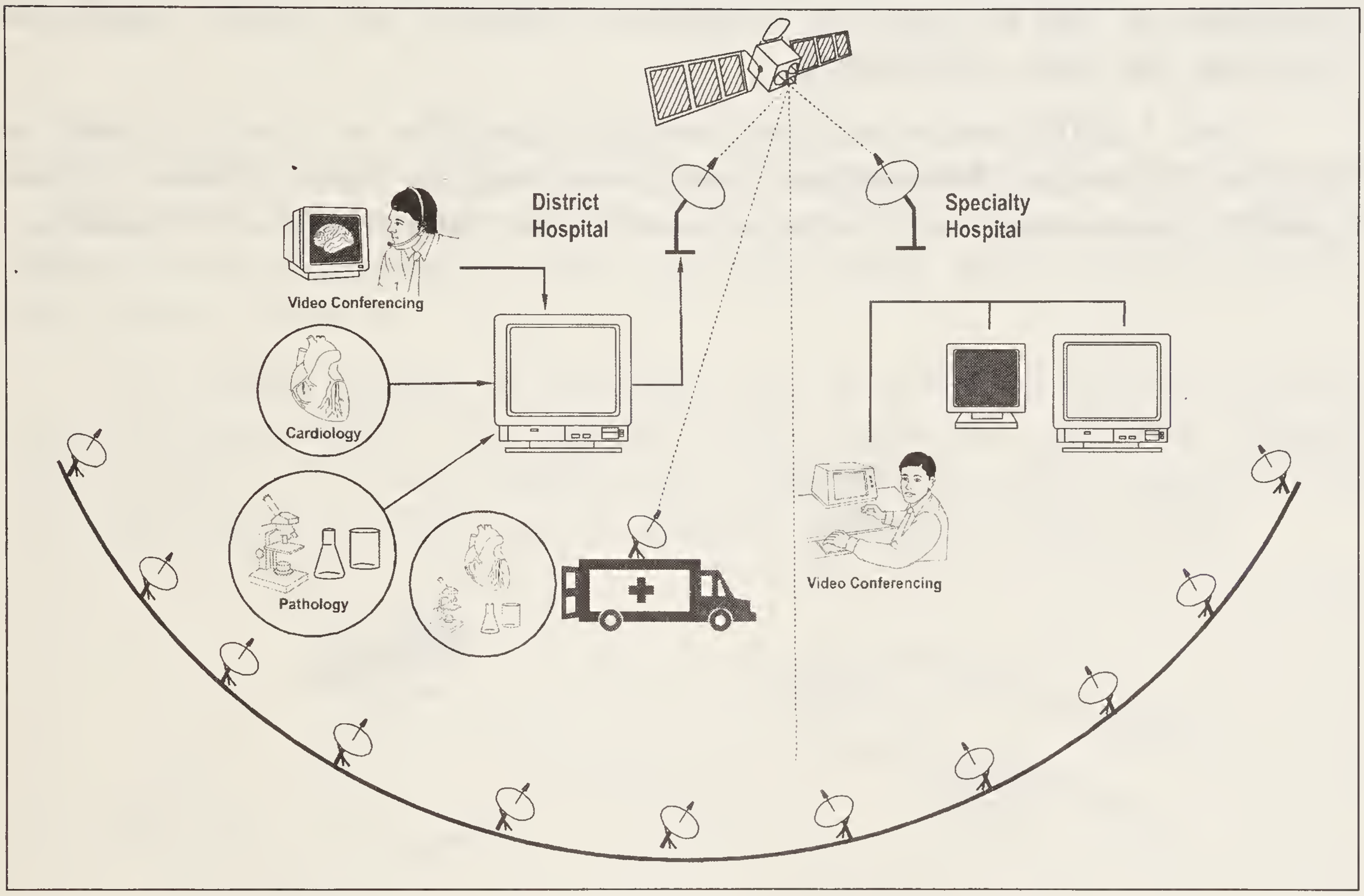


Fig 8.8 : Telemedicine links between district hospitals and specialty medical centres.

Videoconferences are held between cardiologists located in urban specialist hospitals and doctors in district hospitals and often involve women with children in far-flung areas over a satellite link provided by INSAT. The patients benefit from expert views and kind words of comfort and hope.

For instance, the Vivekananda Memorial Hospital at Saragur in Karnataka, set up by a group of young doctors for serving the tribal population, is one of 78 in the country, linked by an INSAT satellite with about 22 super-specialty hospitals.

It was an uphill task in the beginning. Computers in small hospitals were forbidding. The high-tech gadgets such as the X-ray, the ECG and the small satellite terminal seemed too high-tech for villages. But the doctors were confident. The facility has become popular. Those who hesitated were convinced by non-governmental organisations. More remote hospitals and speciality centres in the country have been brought into the network.

ISRO has, on its part, perfected the digital connectivity, which converts the medical images of the patients into a digital signal to be beamed to an INSAT for relay to the super-specialty hospitals. The video link is stable and clear and the interactive mode effective.

Elsewhere, ISRO has brought telemedicine to soldiers in Kargil, pilgrims in Sabarimala as well as people in Andaman and Nicobar, who got the benefit the very next day after the tsunami.

Over 1,20,000 people benefited through telemedicine all over the country in the first 18 months. Telemedicine links are working in Orissa, Assam, Tripura, Ladakh, Lakshadweep, and Andaman and Nicobar islands, besides Karnataka.

31. Satellite-aided Air Traffic

A satellite–based civilian air navigation is getting ready in India for nationwide application. A Master Control Centre will work with eight ground stations in different parts of the country and a land-based uplink station, specially built for the purpose (Fig 8.9).

The satellite payload for the system will be carried by GSAT-4 or one of the forthcoming INSATs. The software for the system has also been developed and accepted. A US firm, Raytheon, has constructed the ground segment as per the specifications of ISRO and the Airports Authority of India (AAI).

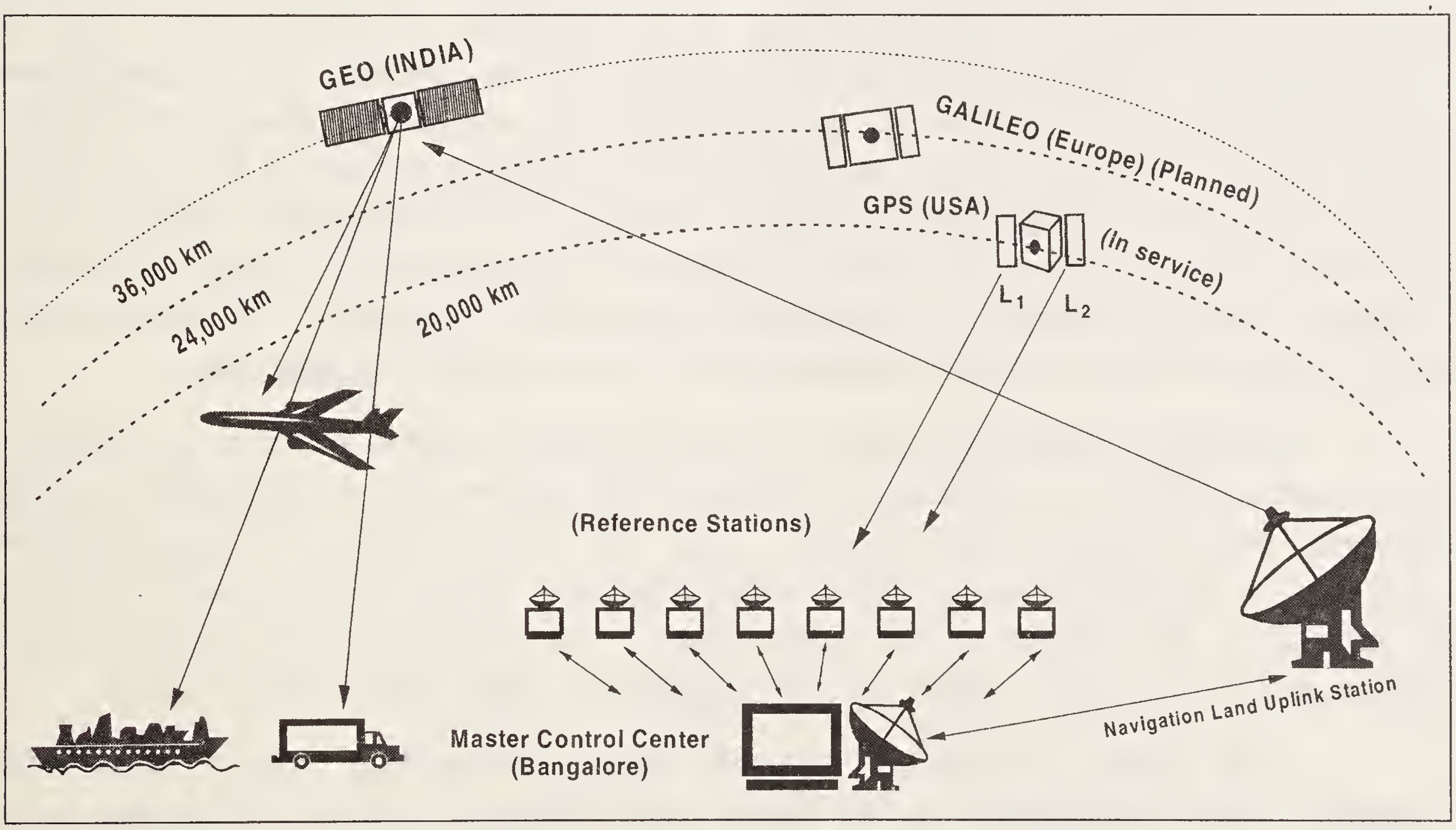


Fig 8.9 : Satellite navigation system for civilian aircraft in India. The ground segment consists of Indian reference stations, uplink stations and a mission control centre, while the space segment will have Indian satellites in the geosynchronous orbit as well as the American GPS and Russian GLONASS satellites in lower orbits.

The system, called GAGAN (for GPS Aided Augmentation Navigation), has been taken up by ISRO as the nodal agency for satellite navigation in the country. The system would continue to make use of GPS or Global Positioning System, operated by the U.S., which today has 29 satellites. The service for civilian use is free. Many countries, including India use it and some have devised technical

means of improving the accuracy of the signals. An alternative system is also preferred.

GPS helps in pinpointing the location of an object or person. The distance to one satellite defines a single common area. The distances to at least three known locations (satellites) from a place are needed to determine the latitude, longitude and the altitude of a place. The accuracy of the distance, based on the time it takes for a signal to travel to the ground, determines how small the common area is. A receiver captures the atomic clock time signals sent from the satellites and converts them into the respective distances. A signal from a fourth satellite is used to improve the time measurement. The satellites are so positioned that at least four of them are visible almost all the time from any point on the Earth. Each satellite is equipped usually with a cesium atomic clock giving exactly 9,192,631,770 pulses a second and it is accurate to within 10 nanoseconds. The signal has the power of only a 25 watt bulb! The satellite signals will indicate its source, position, timing and range. Generally, a correction to the signals is determined separately and transmitted to GPS receivers for incorporation.

The system provides an accuracy of 10 metres, but it is not enough for positional accuracy for aircraft landing. It is important to remove the errors in estimating the vertical and horizontal positions of an aircraft. As a stand-alone system, GPS is not intended to assist civilian air navigation. Hence the United States, Europe and Japan have augmented their navigation systems by introducing signals from the international maritime satellites of INMARSAT. However, the footprint of the European and other augmented signals does not cover the Indian airspace. Hence GAGAN is implemented with the concurrence of GPS system and as recommended by the International Civil Aviation Organisation.

Currently, terrestrial systems in some Indian airports provide an accuracy of 6 metres. But it is difficult to maintain the ground-based instrument landing systems, and moreover each runway needs one such system. We need greater accuracy in estimating the position, navigation and timing in the system. Timing is critical in the system as all calculations of distance are based on the small differences in the time taken by the signals to reach the ground stations.

The quality of service expected from a navigation service must have integrity (trust), availability at all times, and continuity without conditions. It is important to note that the core signals from the GPS satellites are from satellites in orbits at 22,000 km from the Earth, while that from the GSAT will be from the satellite in the geostationary orbit at 36,000 km. Both signals are integrated in modified receivers on the ground. The augmentation is thus a package, consisting of a ground segment and a satellite payload. GAGAN will be available to any civilian aircraft in the Indian airspace.

India is going in for a fully indigenous ground segment backed by seven satellites, as satellite-based navigation is useful not only in aviation but in a wide variety of services like mobile phones, hand-held GPS receivers, highway patrol and monitoring, surveys and maintenance of electricity networks and emergency services where it is critical to know the location without loss of time. Indian industry will have a lot of scope in providing the services based on satellite navigation.

India has signed an accord with Russia for obtaining access to the navigation signals of GLONASS, a Russian satellite-based GPS.

PART - IX

RESOURCE SATELLITES IN ORBIT

32. An Extraordinary Debut

The first Indian satellite, Aryabhata, like the rebel astronomer after whom it was named, broke new ground. To a startled world, it gave a new message: a developing country can enter the Space Age. After a dramatic launch on April 19, 1975, the satellite went into the correct orbit (Fig 9.1). It survived the disastrous snapping of its link with the experimental payload.

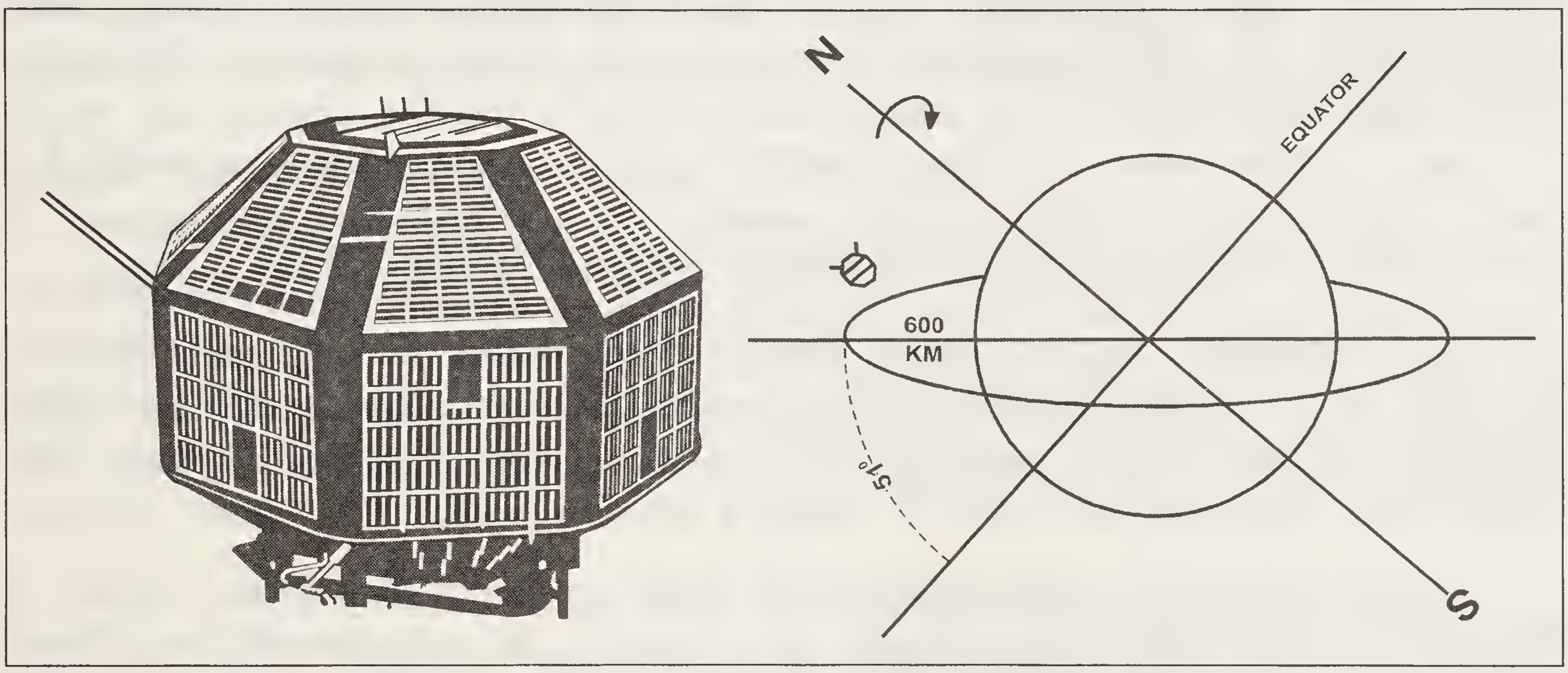


Fig 9.1 : Aryabhata-India's first satellite launched in 1975: It was in orbit for almost 17 years. Designed for an active life of six months, the satellite continued to send data for five years. The satellite was placed into a near Earth circular orbit of 594 km altitude. The satellite's distance from the ground was calculated within one kilometer.

The satellite re-entered the atmosphere on February 10, 1992, after being in orbit for almost 17 years. It had by then completed 92,875 orbits of the Earth. The signals during its last orbit were received for about 30 seconds by the Sriharikota ground station of the ISRO Telemetry, Tracking and Command Network (ISTRAC) at 1827 hours Universal Time (UT). Even after its six-year operating life, Aryabhata was tracked from Sriharikota. Tracking was intensified as the satellite neared its end. Computer programmes developed by ISRO were used to calculate the re-entry data, considering the solar activity which decays the orbit of satellites. In January 1992, the prediction was refined and the data was advanced a little to February 10, 1992 at 2130 hours UT. The final re-entry occurred exactly on this date at 1829 hours UT, when the satellite went silent.

Never was silence so eloquent. To the young experts who made the elaborate calculations, the accuracy of prediction was symbolic of their maturity in handling complex computer programmes. To the not-so-young team that designed the satellite, it was an eloquent testimony of their capability and confidence. The trail-blazing effort ushered in the era of indigenous satellite technology in the country. The re-entry brought back evergreen memories of the pioneering efforts. In those days, Peenya in Bangalore was in the early stage of development. In other words, there were more bullock carts and cycles than cars on the nearby highway. There was practically no infrastructure for making a satellite. A team of 200 dedicated scientists and engineers worked day and night inside the asbestos-roofed sheets, designed, fabricated and tested the satellite in an incredibly short time of about two and a half years.

The team made the best use of technological capabilities in Bangalore and elsewhere in India. Several organisations were involved: The Hindustan Aeronautics Limited, the Bharat Electronics Limited, the Electronics and Radar Development Establishment, the Indian Institute of Science, and private companies. The goals were simple and clear, viz. to design and fabricate a satellite system that works in space; to learn how to conduct satellite operations; to set up ground support and to establish the facilities. As the country did not have a suitable rocket, it was decided to accept an offer from the Russians to launch the satellite.

An agreement signed between ISRO and the Soviet Academy of Sciences on May 10, 1972 provided for Russian panels, batteries, spin systems and tape recorders, besides launch assistance and telemetry data reception support. The launch was scheduled for 1974-75 using a Russian rocket.

The satellite was quasi-spherical in shape with 26 flat faces, having a diameter of 1.6 metres and a height of 1.2 metres. It was powered by silicon solar cell arrays and nickel-cadmium batteries. Its temperature was adjusted by passive thermal control. The satellite was spin-stabilised. In order to prevent it from tumbling, it was spun. The torque for this purpose was given by nitrogen gas jets activated on command from six spherical titanium bottles. Each bottle was filled to a pressure of 200 atmospheres of dry nitrogen gas which escaped through two nozzles. The first two bottles were opened by a pre-programmed command after the injection of the satellite into its orbit. Later, the commands were issued from the ground. The spin rate was maintained. The orientation was measured by a set of magnetometers that sensed the Earth's magnetic field just like a magnetic compass, providing two reference directions. Another reference direction was given by a digital Sun sensor that measured the angle between the spin axis of the satellite and the Sun-satellite line. The directions were accurate to about a degree.

When the satellite structure was designed, it was realised that special test facilities were required to evaluate them. Spin loads had to be simulated. Its centre of gravity had to be measured. Extreme vacuum and temperatures (plus 100° C to minus 100° C) had to be created. In order to simulate some of these conditions, a thermovac chamber was set up. This was the country's first venture. The expertise available at the Bhabha Atomic Research Centre and the Electronics Corporation of India Ltd. was utilised to build it. A tracking system with telecommand was designed and installed at Sriharikota. A small ground station was set up at Peenya itself to receive satellite signals. Soon fabrication began. A scaled-down model of various systems was sent up in a balloon and tested. A full-scale model was then made. A mechanical mock-up was meanwhile tested to evaluate the design concepts. Prototype models were made and tested.

Later, a flight model and a standby were built. The satellite was taken to Russia and tested again to ensure that it could go in its rocket. It was launched on April 19, 1975 into a near-Earth circular orbit of 594 km altitude, at an inclination of 50.4° to the equator. It orbited the Earth once every 96.41 minutes.

A Bonus and a Snag

The passive thermal control system of Aryabhata worked within plus or minus two degrees Centigrade of the predicted values. When the outside temperature varied from 80° C to minus 50° C as the spacecraft turned from the Sun-lit side of the Earth to darkness, the internal temperature of the satellite was kept within 0° C and 40° C. Special paints, given inside on the basis of computer calculations, worked well.

In one year in orbit, the spin rate of the spacecraft decayed from 50 rpm to 5 rpm. The rate of decay was lower than expected. This meant a bonus in the form of conservation of the onboard gas. The magnetometers, Sun sensors and other devices to determine the attitude of the satellite worked to an accuracy of plus or minus one degree. The telemetry systems both in Sriharikota and Bearslake near Moscow, worked satisfactorily. The error rate in data transmission was just 0.05 per cent including errors in the ground segment. Thousands of commands were sent successfully to the satellite. They all worked except in one area.

The failure related to a regulator, one of 14 which supplied power to all the three scientific experiments. In the 41st orbit, the regulator went out of order. The power system itself was normal. The solar array and the battery generated power as expected. The experiments were really piggy-back devices as the basic objective was to develop satellite technology. A section of the Press ridiculed the whole mission as a failure. But Aryabhata rolled on to become a legend. Designed for an active life of only six months, the satellite continued in good shape. The

flow of data stopped in April 1980, when it had completed 32,527 revolutions around the Earth, of which 3,500 came within the visibility of Indian stations. Sputnik-1, the world's first satellite in orbit, went silent after 21 days!

The satellite's distance from the ground was calculated within one km. Its speed which was nominally 8 km a second, was estimated within 20 metres a second. As the Earth rotated, the satellite's path from orbit to orbit changed by about 2,500 km. The satellite's magnetic and Sun sensor worked well. The satellite's orientation was measured with an accuracy of 1° as against the original requirement of 2° to 2.5°. The newly built Yagi antenna in Sriharikota received the signal when the satellite was 2,500 km away.

Even though the primary aim was the development of satellite technology and on-orbit maintenance, some communication experiments were also done. In one of them, electro-cardiogram (ECG) data were transmitted from Sriharikota to Bangalore.

In another experiment, weather information from a standard data collection platform was transmitted.

In the 17 years of Aryabhata's orbit, India's space programme did not remain static; it went through a rising learning curve, when two generations of scientists and engineers acquired enough maturity and skill to turn failures into stepping stones towards success.

33. A Series of Resource Satellites

Encouraged by the success of the first satellite, ISRO drew up a more ambitious design for the second. It was aimed at utilisation of satellite technology for development. Accordingly, it was decided that the satellite would carry remote sensing sensors which would detect and assess natural resources from space. It took nearly four years to develop it. The satellite was launched by the Russians and was put into orbit on June 7, 1979.

The satellite weighed 444 kg with a diameter of 1.55 m and height of 1.18 m. The 26-faced, quasi-spherical satellite had two television cameras and three microwave radiometers for the remote sensing mission. It was named Bhaskara, after a leading Indian astronomer of the sixth century AD and another eminent mathematician of the twelfth century.

In view of the television and other sensors aboard, the spin system was made stronger. Its spin rate was controlled from the ground by the use of reaction gas jets on the satellite. The gas needed for one year of operational life was stored on board. Its spin also ensured its thermal equilibrium. Passive thermal control, developed by ISRO, maintained internal temperature between 0° and 40° C. In order to enable the TV camera and other sensors to pinpoint the target area, a horizon crossing sensor was installed to identify the infrared horizon of the Earth from its near circular orbit of 557x572 km at an inclination of 50.7°.

Bhaskara was more sophisticated than Aryabhata. For Aryabhata, 35 different commands could be sent, whereas for Bhaskara, their number was 200. Data from Aryabhata came at 2,560 bits per second when the tape recorders played back recorded information. In Bhaskara, data flow was as high as 91,000 bits per second. Data were transmitted at this rate during its pass over Sriharikota, which lasted about 10 to 15 minutes. Some silicon solar cells and solar panels, indigenously developed, were tried. The spin axis was altered during the mission to gather more data. When the TV camera did not work, simulation studies were conducted on ground, before finding the cause. The problem, though proved to be transient, gave the engineers a chance to prove their systems all over again.

Careful use of onboard gas and system management extended the mission life of the satellite. The mission ended only on August 1, 1981, after about two

years in orbit. By April that year, the satellite had completed 10,000 orbits including 638 tracked by Indian stations. During 184 orbits, the satellite's TV cameras operated and the entire country was covered thrice. Even after the end of its useful life, the satellite's spin stability was maintained and the silent craft was tracked once a week.

Bhaskara-II

An improved version of Bhaskara I was fabricated based on the lessons learnt from the first remote-sensing mission. The power distribution systems connecting TV were made foolproof. Indigenous thermal coatings, solar cells and panels were used. The satellite was launched on 20 November 1981 by the Russians. Ground stations at Sriharikota and Ahmedabad handled the reception of data and control. The satellite attained the planned near-Earth orbit of about 525 km with an inclination of 50.7°. Its spin axis was brought perpendicular to the orbit plane to facilitate the deployment of TV camera. The satellite re-entered the Earth's atmosphere on 30 November 1991, after 10 years in orbit.

Rohini Satellites

Though Russian rockets were available, ISRO developed a satellite that could be orbited by an Indian rocket. The result was Rohini Satellite (RS-1), the first to be launched by an Indian rocket. It was boosted by the second experimental SLV-3 in 1980. Its main object was to monitor the fourth stage performance of the launcher. The performance of the 35 kg satellite exceeded the expectations. It was launched into a slightly higher orbit than predicted. It was placed in an elliptical orbit of 325 km by 950 km with a period of 97 minutes instead of the planned 276 km by 472 km. Being in a higher orbit, its decay was delayed. Ground stations in Thiruvananthapuram, Sriharikota, Car Nicobar and Fiji received good signals. Telemetry data from it were processed by computer systems in Sriharikota and its orbital parameters were predicted. After completion of the mission, RS-1 re-entered the Earth's atmosphere on 24 July 1981, exceeding the targeted period of 100 days.

Even as Rohini-I went into orbit, work began on Rohini-II at the ISRO Satellite Centre, Bangalore. The second satellite was launched in the first development mission of SLV-3 on 31 May 1981. The 41-kg satellite was designed to have spin axis orientation manoeuvres. Designed to be in orbit for 300 days, it went into orbit 12 minutes and 30 seconds after lift-off.

The satellite carried a new remote sensing device called landmark sensor. But the satellite was injected into a lower orbit and, as a result, it could not stand the pull of the atmosphere for a long time. It heated up and re-entered the atmosphere only nine days after the launch. Though the spin rate was brought

down from 112 rpm to 60 rpm, it was still high for the operation of the payload. The specified spin rate was 8 to 10 rpm. However, the sensor was switched on at 60 rpm itself. An analysis of the pictures revealed that the sensor had functioned well.

The SROSS Series

ISRO continued to design and develop a series of small satellites for conducting experiments in basic space science, space technology and applications known as the Stretched Rohini Satellite Series (SROSS). The satellites can take payloads in the range of 15 to 35 kg (Fig 9.2).

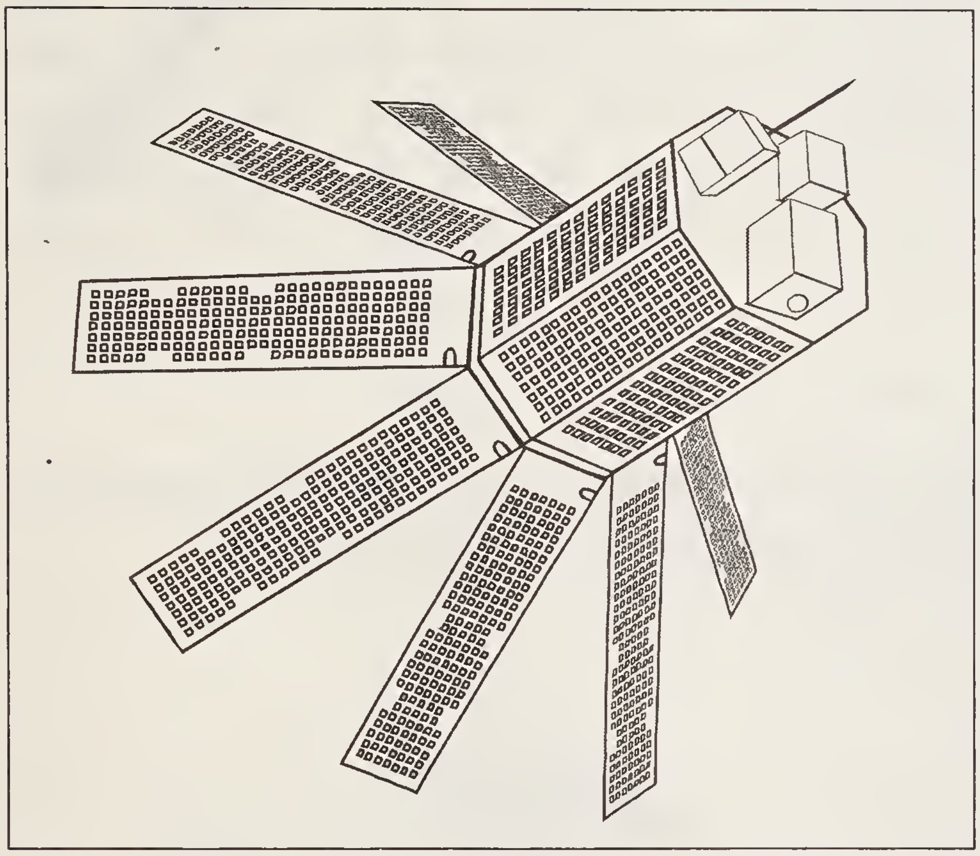


Fig 9.2 : Stretched Rohini Satellite Series (SROSS): Designed mainly for technological or appliction missions, they enable designers to pretest advanced techniques.

Octagonal in shape, a SROSS satellite can have either body-mounted or deployable solar panels on all sides. Its attitude and orbit control system has momentum wheels and reaction control systems. Silicon solar cells provide the power, backed up by nickel-cadmium batteries. Despite the severe constraints on volume and weight (150 kg), users can get the benefit of almost all the features normally available in the state-of-the-art spacecraft.

The first in the series, SROSS-1, was designed to monitor the dynamic environment of the launch vehicle, particularly the performance of the fourth stage and to conduct a laser tracking experiment. The tracking was to be done by the optical tracking facility at Kavalur and by some international ground stations. The spacecraft also had an experimental payload to measure celestial gamma-ray bursts. The payload for launch vehicle monitoring had a velocity increment determination experiment and another for validating the design of the payload.

The second in the series, SROSS-2 was to carry a remote sensing payload called the monocular electro-optic stereo scanner, jointly developed with the German Aerospace Research Establishment. SROSS-1 and –2 could not be put into orbit because of ASLV failures. SROSS-C, carried by ASLV-D3, had two payloads, one for measuring gamma ray bursts and the other for measuring the density and temperature of electrons and ions in the ionosphere over equatorial and low

latitudes. Its attitude and orbit control system comprised a Sun sensor, magnetometers, a nutation (wobble) damper and magnetic torquers (for controlling the spin rate).

SROSS-C2, which was put into orbit by ASLV-D4, carried for the first time the indigenously developed nickel-cadmium batteries. The space-qualified battery cells were developed by VSSC and tested at the ISRO Satellite Centre, Bangalore. The 113 kg satellite evaluated the launch vehicle performance and carried payloads to detect gamma ray bursts and to study the upper ionosphere.

The satellite was launched on May 4, 1994. It went into an orbit of about 437 km (perigee) and 939 km (apogee). From July 1, 1994 the orbit was manoeuvred continuously for a week and given the intended height of 429 km (perigee) and 628 km (apogee). Scientific data were collected from both the payloads before initiating the changes in the orbit. At the end of the manoeuvre, about 1.3 kg of fuel remained out of the 5 kg used at the start of the mission for routine orientation control.

Advanced Sensors

Since PSLV was not ready, IRS-1A was launched by a Russian launcher, Vostak, from Baikonur in the Kazakhstan Republic in 1988 (Fig 9.3).

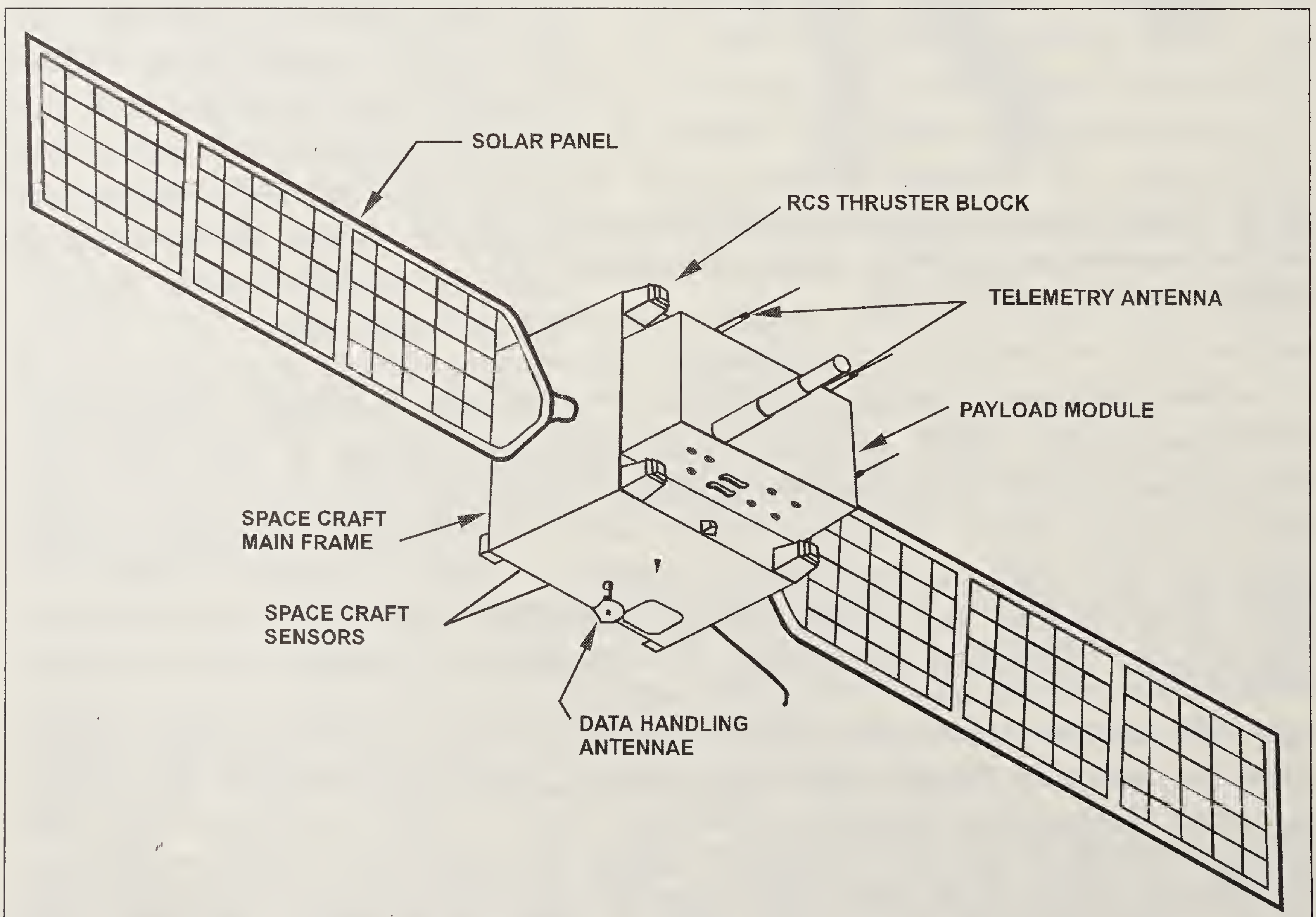


Fig 9.3 : Components of IRS-1A and 1B. These satellites far exceeded their design life and provided high-quality imageries useful for a variety of applications.

An identical satellite, IRS-1B, was launched in 1991, also by a Russian rocket. Data from this satellite were received not only in Shadnagar near Hyderabad but by a US ground station at Norman, Oklahoma for marketing the data worldwide.

IRS-1 weighed 975 kg including 80 kg of hydrazine for orbit control. It had deployable and sun-tracking panels for generation of 709 watts (at the end of life). The aluminium structure had many thermal control devices including tapes, paint and heaters. The temperature on board was designed to be around 20° (plus or minus 5°) for the imaging sensors electro-optics and 0-40° for the electronic packages.

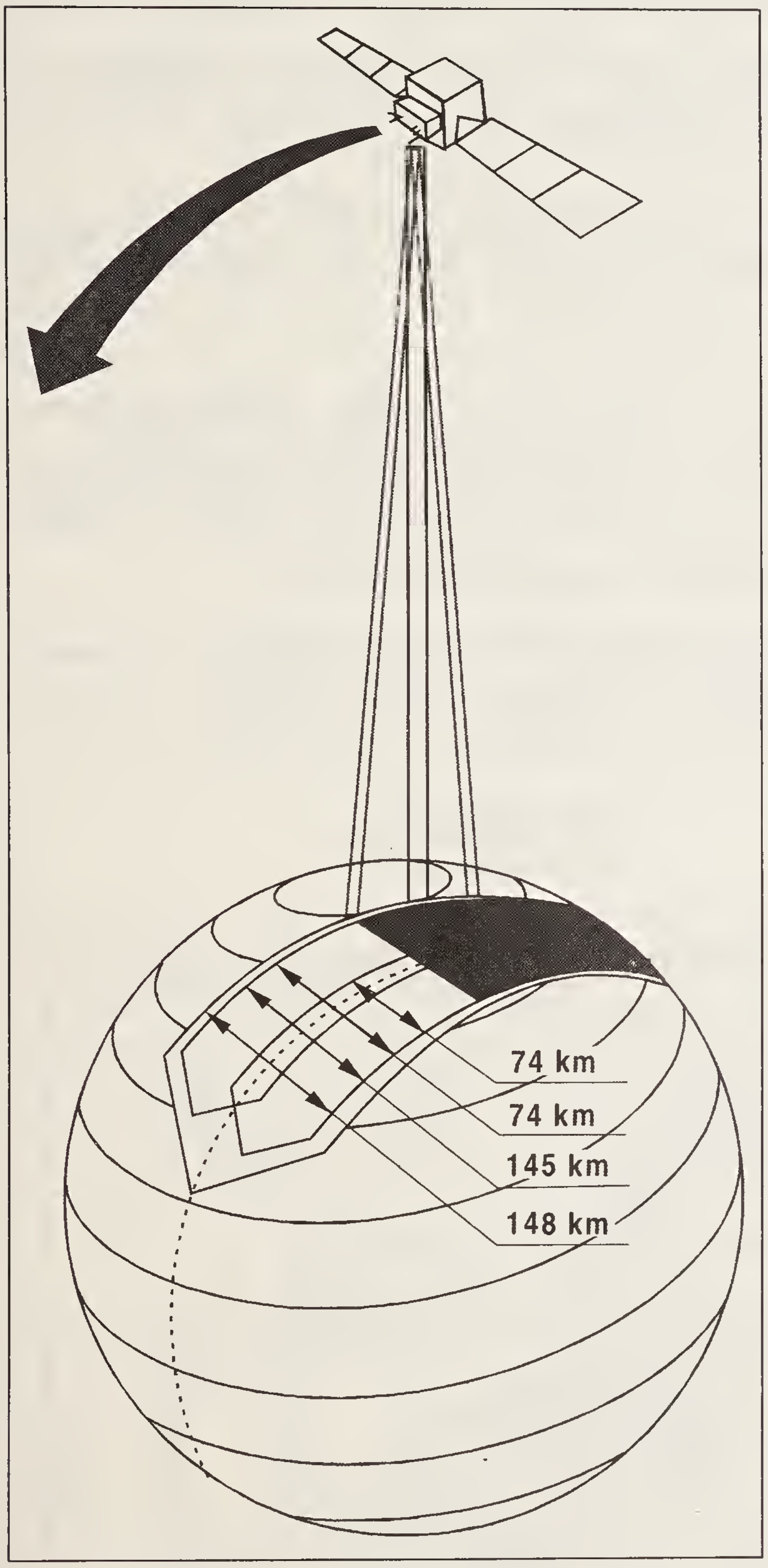


Fig 9.4 : Two types of imaging sensors, one with a spatial resolution of 72.5m and the other with two separate sensors with a spatial resolution of 36.25 m each. One sensor provides a swath of 148km, while another traces a composite swath of 145km.

The attitude and orbit control had infrared horizon sensors, a star sensor, sun sensors and gyros, besides four reaction wheels, magnetic torquers and hydrazine thrusters. The accuracy of the orbit was designed to be 1 km and that of attitude, 0.1°. The equatorial crossing time of the descending node was fixed to meet the user requirements.

Several ISRO satellites carry advanced imaging sensors, viz., Liner Imaging Self Scanners (LISS-1 and LISS II A/B) and can handle high bit rate image transmission up to 20 mega bits per second.

IRS-1A and IRS-1B had three scanners (LISS) each; one provided a spatial resolution of 72.5 metres and a ground swath of 148 km. The other two were identical but were placed to provide individual swaths of 74 km on either side of the ground track, with a 3 km overlap between the two swaths. Thus the scanners together provided a total swath of 145 km. The resolution of each was 36.5 km (Fig 9.4).

The imaging sensors scanned the ground as a push-broom line by line as the satellite moves.

Both IRS-1A and 1B exceeded their design life of three years. With two satellites, the capacity revisit went up to 11 days. IRS-P2, launched by PSLV-D2 in 1994 covered the whole country every 24 days. Right from the beginning, the end use was survey and management of natural resources of the country in important areas such as agriculture, geology, and hydrology.

IRS-1C

In order to continue and strengthen the IRS system, the development of the second generation satellites, IRS-1C and IRS-1D, was taken up.

IRS-1C, the second generation Indian remote sensing satellite, was designed for a global mission. Its data were to made available all over the world by establishing a network of ground stations (Fig 9.5).

Weighing about 1250 kg, IRS-1C, was placed in a polar sunsnychronous orbit of 817 km by a Russian Molniya booster in December, 1995 from Baikonur. The satellite exceeded its design life of three years and crossed ten years in orbit. In December, 2005, it completed 60,000 orbits of the Earth.

The launch was smooth and the satellite was placed into orbit 15 minutes after lift-off around 21° North latitude. About 93 seconds after injection into the

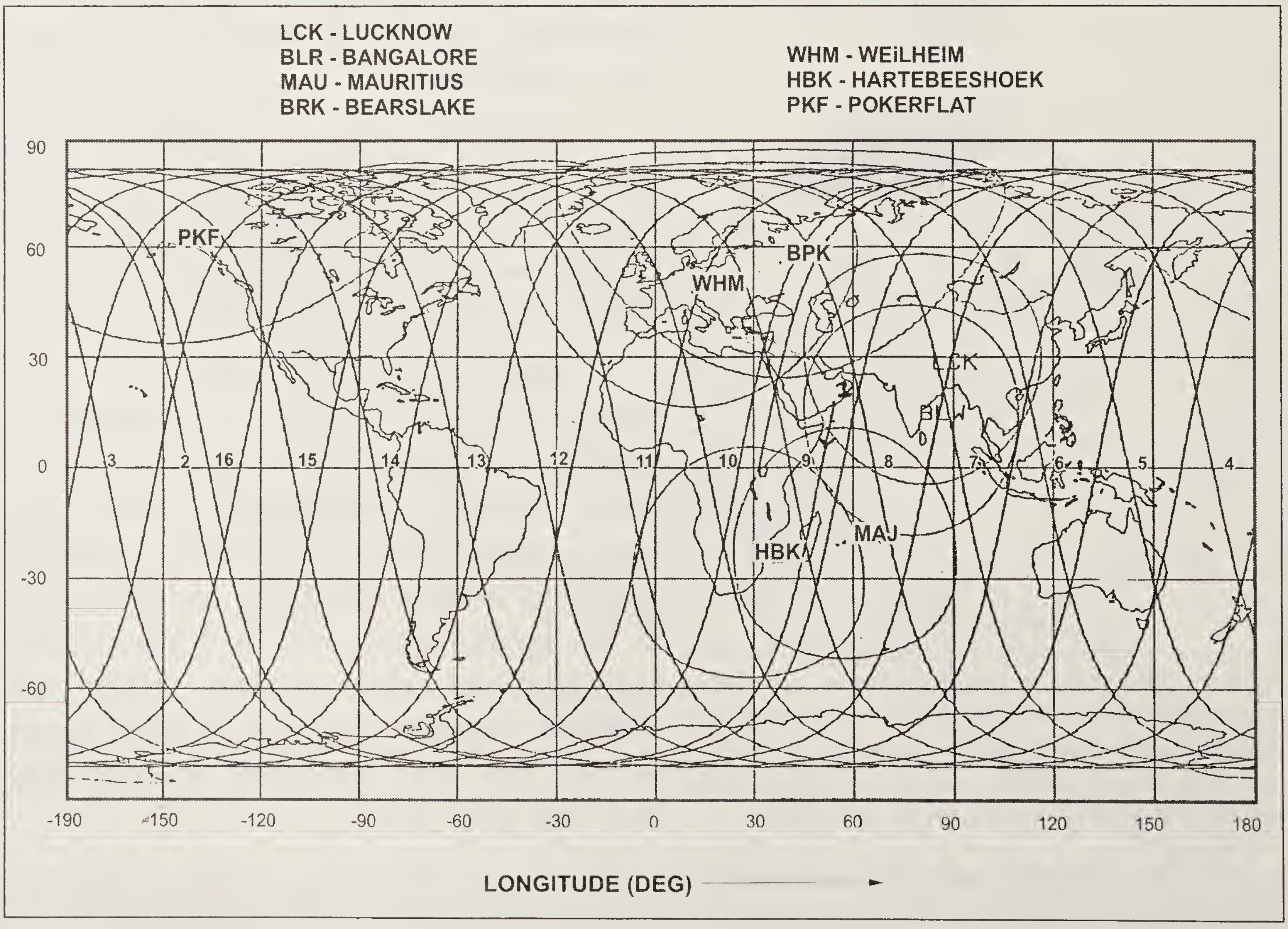


Fig 9.5 : Ground track of IRS - 1C. It is being monitored by Indian and foreign Earth centres.

orbit, the two solar panels were automatically deployed by onboard timers. Commands were issued from the Mauritius station of ISRO to initiate Sun acquisition. And the solar panels were rotated to face the Sun. The satellite went through the first eclipse and later reacquired the Sun. The orbit was locked to the specific path of IRS-1C from 10 January 1996. All the payloads worked as specified. The onboard tape-recorder - the first to be placed on an Indian remote sensing satellite - started functioning satisfactorily. It was capable of 24 minutes of recording, when data were not being transmitted in real time. The recorded data were downloaded at Shadnagar near Hyderabad regularly.

The satellite (IRS-1C) took 24 days to complete a cycle of 341 orbits. Each orbit, completed in 101.35 minutes, was shifted westward by 2,820 km. The same spot was revisited once in five days by the PAN camera, when the distance between Day 1 and Day 5 was 117.5 km.

IRS-1C had improved spatial resolution, enhanced spectral coverage, more frequent revisits and stereo viewing capability (Fig 9.6). The main payloads were:

- a multispectral linear imaging self-scanner LISS-III operating in the visible and near infrared bands with a spatial resolution of about 23.5 m (with a swath of 141 km) and a short wave infrared (SWIR) band with a resolution of 70.5 m (and a swath of 148 km),

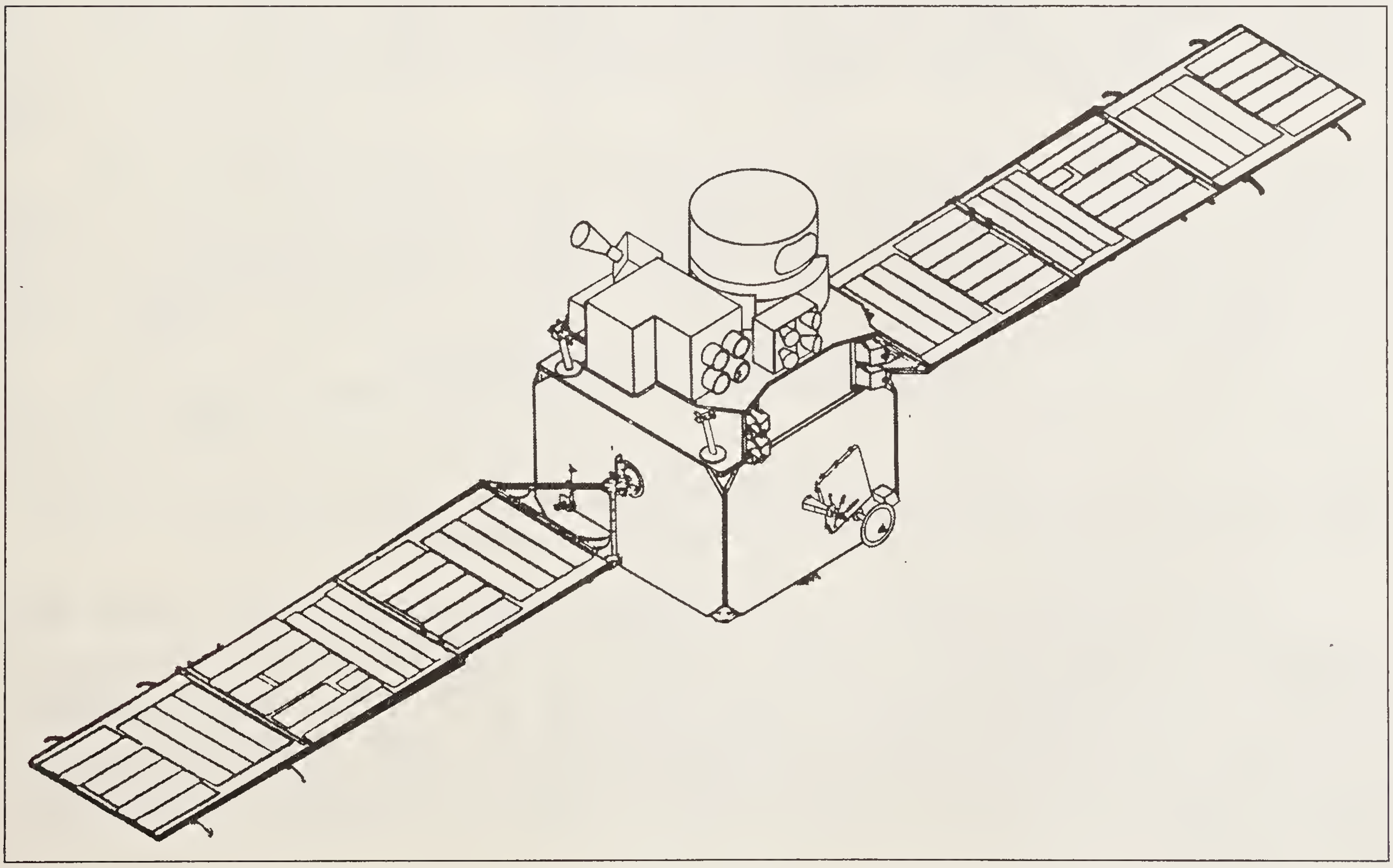


Fig 9.6 : IRS-1C has payloads with enhanced capabilities compared with IRS-1A/1B in terms of spatial resolution, spectral bands, and revisit capability. Onboard recording of data was done, its panchromatic (PAN) camera gave the highest spatial resolution offered by any civilian satellite in orbit (in 1996).

- a panchromatic camera (PAN) with a resolution of 5.8 m with stereo viewing capability, covering a swath of 70 km, and
- a wide field sensor (WIFS) operated in the visible and near-infrared bands with a resolution of 188.3 m, covering a wide swath of 810 km.

All the cameras operated in the push-broom scanning mode with charge coupled devices. PAN is a high-resolution camera operating in a single panchromatic spectral band. It was steerable up to plus or minus 26° in the across-track direction. This mode of viewing from two angles provided stereoscopic imagery of an elevated terrain (Fig 9.7).

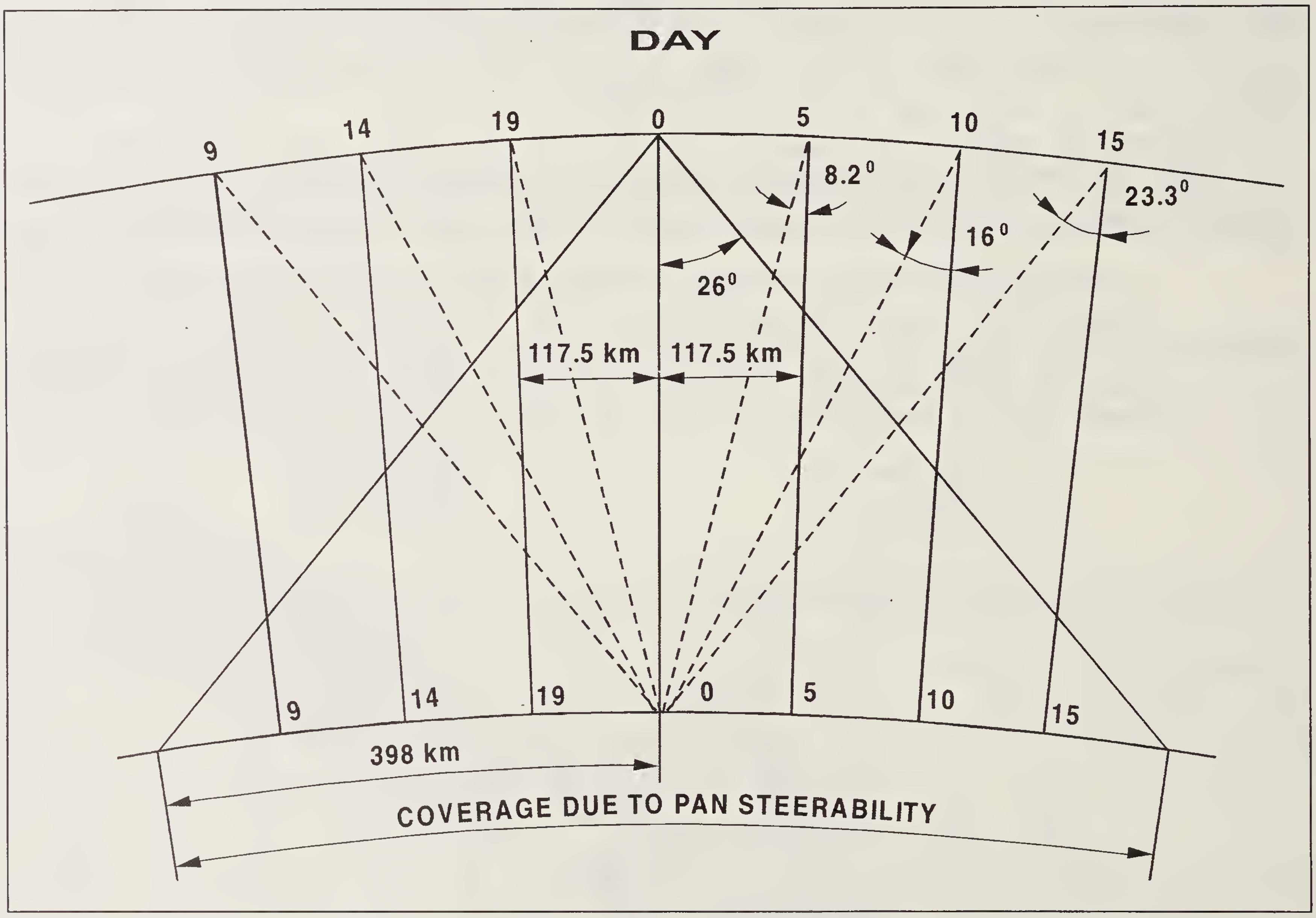


Fig 9.7 : A new feature in IRS-IC was the capability of its panchromatic camera to steer upto 26° in across-the-track direction, to provide stereo images of the terrain with a revisit frequency of 5 days.

LISS-III camera operated in four spectral bands: three in the visible and near-infrared range identical to bands 2.3 and 4 of IRS-1A and 1B, and one in the short wave infrared (band 5). Both PAN and WIFS had a revisit capability of 5 days. The data from the two spectral bands in which WIFS operates are used to derive the vegetation index which is useful in assessing the possibility of a drought.

The payload platform was isolated from the main platform of the satellite. The attitude measurement sensors included a Sun sensor, Earth sensors with

onboard correction logic, a magnetometer and dynamically tuned gyros. A star sensor was used for checking the attitude determination very accurately. The controls included magnetic torquers and hydrazine thrusters. The pointing accuracy designed was 0.15° in the pitch and roll axes and 0.2° in the yaw axis. The attitude and orbit control system was based on a zero-momentum system using four reaction wheels, three of which were mounted in the orthogonal direction and the fourth skewed at an angle of 54.7° with all the three axes.

IRS-P2 (1994) and IRS-P3 (1996), launched by PSLV-D2 and D3, respectively were designed to carry out some experiments, even as they validated the capability of their launchers.

IRS-P3: Indian and German Payloads

The 930-kg IRS-P3, launched by PSLV-D3 in 1996 carried two remote sensing payloads and one X-ray detector. One of the remote sensing payloads was a Wide Field Sensor (WIFS), similar to that of IRS-1C, but with an additional Short Wave Infrared band (1.55-1.70 micrometres) which is sensitive to the moisture content of crops. Hence it provided additional data for assessing crop conditions. The band was also useful in differentiating snow and cloud cover and in assessing flood damage. The applications include mapping of chlorophyll in the sea, sediment transport at river mounts, and biomass monitoring in the ocean. With a swath of 810 km, the WIFS in IRS-P3 covered a larger area than the SWIR sensor in IRS-1C.

The second remote sensing payload was a Modular Optoelectronic Scanner (MOS) of the German Space Agency. MOS had three modules, one of which (Module B) was designed to study primarily ocean related features in 13 narrow spectral bands. The other modules were designed to correct the B module.

This was followed up by IRS-1D in 1997. It had three cameras, with spatial resolutions ranging from 5.8 m to 188 m.

34. Oceansat and Cartosat

India's 7,500 km coastline supports considerable marine resources. In the 1990s India conducted a major programme known as Marine Satellite Information Services to develop methodologies for retrieval of parameters relating to the ocean. Using the US NOAA satellite data, estimates of sea surface temperatures were made. Mapping of coastal zones at different scales was done with Indian Remote Sensing satellites. Data from foreign satellites were also utilised to develop certain techniques. The advent of dedicated Indian satellites is expected to strengthen space-based ocean remote sensing.

Satellite data have been found useful in identifying potential fishing zones in coastal waters, exploration of deep sea fishery resources, and in the prediction

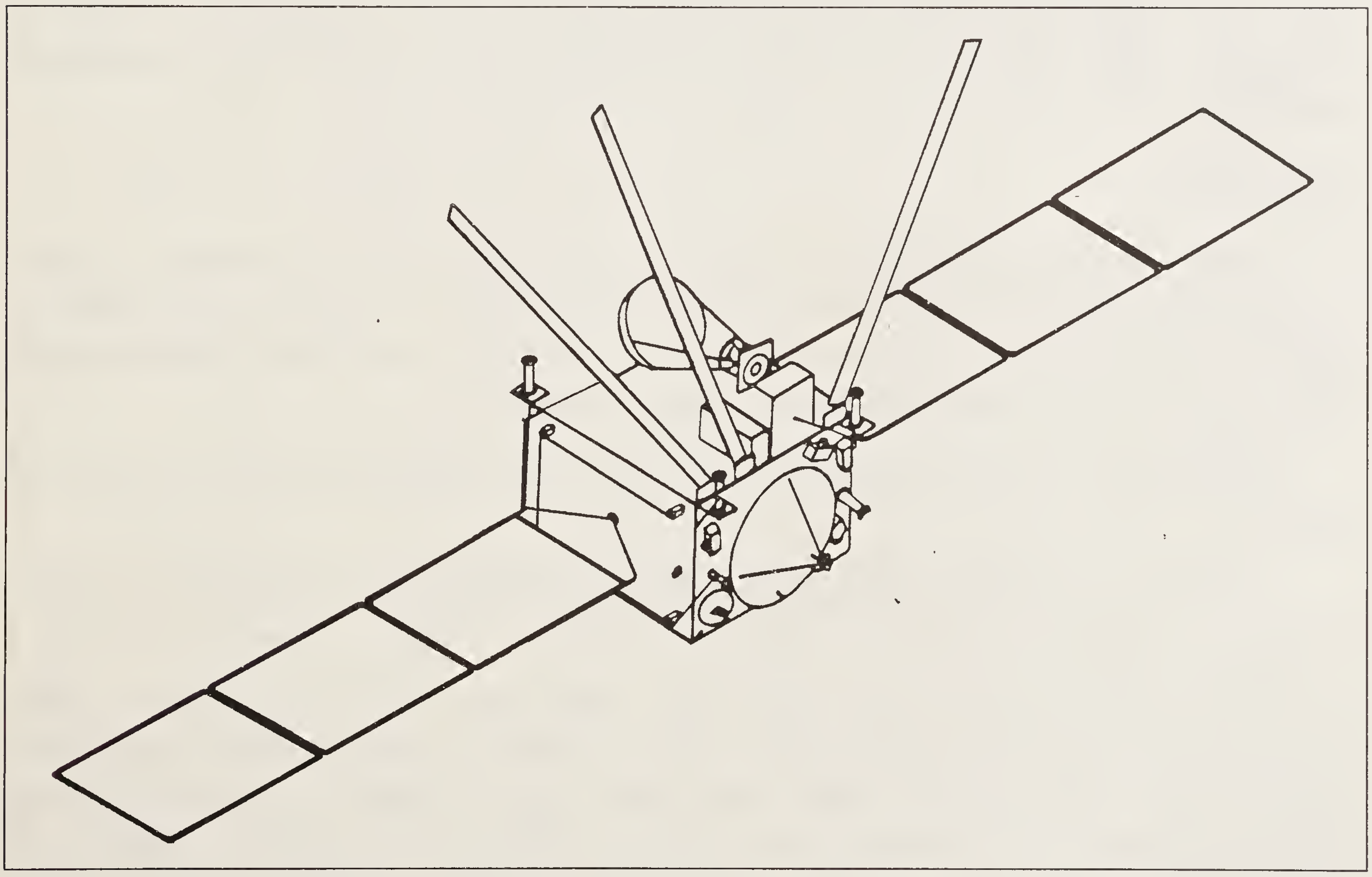


Fig 9.8 : Oceansat-1: designed to study physical and biological aspects of the ocean.

of shoreline changes, circulation and dispersal pattern, sediment movement, marine pollution and in coral reef studies.

ISRO therefore decided to design a series of ocean satellites. The first in the series, Oceansat-1, was launched in 1999 (Fig 9.8).

The satellite has two payloads: Ocean Colour Monitor (OCM) and a multi-frequency scanning microwave radiometer (MSMR). The OCM, a solid-state camera, operates in eight narrow channels in the visible and near infrared region of the spectrum. It collects data on chlorophyll concentration, detects and monitors phytoplankton blooms, atmospheric aerosols and suspended sediments to water. The identification of phytoplankton is based on optical properties of seawater caused by chlorophyll-A, the primary photosynthetic pigment. The sensor can be tilted by plus or minus 20° to avoid sun glint, while collecting data. Phytoplankton supports all marine life and acts as a biological pump in the oceans.

The MSMR operates in four microwave frequencies and can penetrate clouds. The combination of optical and microwave sensors monitoring the same area concurrently would help in the study of surface currents.

Orbiting at 720 km, the satellite can see the same area once in two days. MSMR has been configured in such a way that it would have the same angle, as it scans the area within its footprint.

The radiation received from the sea surface is partly due to self-emission from the scene and partly due to the reflected radiation originating from the atmosphere. The challenge is to assess and eliminate the impact of the atmospheric constituents.

Oceansat-2

Oceansat-2 is designed for ocean-related studies. An ocean colour monitor (OCM) and a pencil beam scatterometer will be placed on board. In addition, an Italian radio occultation sounder for identifying fishing zones, sea level forecasting and weather and climate studies will be included.

Oceansat-2 will be launched into a near polar sunsynchronous orbit of 720 km.

OCM is a 8-band multispectral camera operating in the visible and near IR spectral range. It can be tilted up to plus 20 degrees along the track.

OCM has an active microwave radar, operating in the Ku-band (13.5 GHz) and giving a ground resolution cell of 50 x 50 km. A parabolic dish antenna is continuously rotated at 20.5 rpm. Two beams are generated to scan the ground surface and the back scattered power in each beam is measured to derive wind information.

A Technology Experiment Satellite was launched in 2001 to validate and demonstrate technologies for cartographic applications. The spatial resolution of the

imagery taken was one metre. The satellite also tried improvised reaction wheels with a single propellant tank and attitude and orbit control systems.

Resourcesat-1, an advanced remote sensing satellite of ISRO, was launched in 2003. A PSLV rocket placed it in 820 km polar sunsynchronous orbit. It was a replacement of IRS-1C and –1D. It has advanced sensors for land and ocean resource applications. It carries three cameras: LISS-4 in three bands in the visible and the near infrared region with a 5.8m resolution. The camera is steerable plus or minus 26 degrees across the track to obtain stereoscopic images revisiting the same place every five days.

Another camera, LISS-3, can take imageries in the short wave infrared as well as in the visible and near infrared with a medium resolution of 23.5 m in a 142 km swath. The third camera, an Advanced Wide Field Sensor, has a 56 m spatial resolution in similar spectral bands in the visible and infrared. The satellite has a solid state recorder for storing images for later download.

Small changes in the sea level may indicate big changes in the offing. Radar altimeters on board satellites play a key role in detecting the rise in the sea level. ISRO and the French Space Agency are considering a radar altimeter and a data relay device to be placed on an Indian satellite as a joint project.

Impact of the Sea Level and Global Warming

Scientists have revealed that the rise in the sea levels in the recent past has been quite fast, compared to the previous centuries, leading to unusual climate and rainfall.

Even a few inches of rise in the sea level can play havoc. Changes in the sea level have therefore become one of the closely watched features.

Thanks to satellites and advanced sensors, it is possible nowadays to measure the rise in the sea level with extraordinary accuracy. The measurement is made by satellite radar altimeters. They send radar signals down to the sea surface and detect the returning signals and measure the corresponding slight variations in the sea level.

The height of a satellite is nowadays known accurately. Hence it is fairly easy to measure the range between the satellite and the sea surface. But the depth of the sea is not known accurately everywhere. Hence the sea surface height is calculated with regard to a terrestrial reference, which is actually an imaginary surface that approximates the shape of the Earth. This is a sphere flattened at the poles, called the

Contd...

reference ellipsoid. By deducting the distance of the satellite to the sea surface, from the satellite's range to the ellipsoid, the height of the sea surface is calculated.

Several French and European satellites have altimeters to measure the sea surface: TOPEX-POSEIDON (1992), a joint mission of NASA and CNES (French National Space Agency), JASON-1 (2001), and three European Earth satellites, ERS-1 and –2 and ENVISAT. Their data are in fact distributed to interested agencies. The data are useful in the study of climate change and weather prediction, mean sea level rise and global warming.

JASON-1 can measure the sea surface with an accuracy of two centimetres. An advanced version, JASON-2, is due for launch in April 2008. It will measure the sea surface in real time. This would be a gain, as it took five hours to process the data from JASON-1 recently.

It may be recalled that TOPEX-POSEIDON, JASON-1 ENVISAT-1 and a US Navy satellite, which were in orbit, happened to be above the Indian Ocean just after the tsunami struck the coast in 2004. They did measure the sea level surface.

A rise in the sea level is believed to be linked to global warming, which in turn is related to the accumulation of carbon dioxide in the atmosphere? And here is a cause for concern. Several scientists have pointed out that the current levels of carbon dioxide and methane in the atmosphere have been the highest in the past 6,50,000 years. This is the conclusion of the latest European studies based on ice cubes taken from a depth of about three kilometres below the surface in Antarctica. Digging to this order of depth, it is stated, is equal to going 9,00,000 years back in time, as the gas bubbles trapped inside the ice would reveal the typical carbon dioxide and methane that prevailed at that time. Based on the study, scientists state that the carbon dioxide has increased by 30 per cent and methane by 130 per cent more than at any time in the last 6,50,000 years. What is more, carbon dioxide has increased 200 times faster during the same period.

The latest study is the second of its kind. The first revealed ice cubes under the sea that were dated 4,20,000 years. This period appears to be significant, as around this time, the Earth's climate pattern began to undergo definite cycles of warm and cold conditions. A majority of climate scientists agree that there exists a connection between the level of carbon dioxide and temperature.

Climate study is sophisticated, as it has to consider several parameters other than just temperature and the sea level. Moreover, the tropics have not been studied in depth. A satellite under an Indo-French mission called Megha-Trophique is designed to fill the gap. ISRO and CNES (the French Space Agency) have signed an accord for the mission due in 2008 or a year later.

ISRO will build a satellite for the purpose and launch it with a PSLV and control it at 867 km in an inclined orbit around the Earth. The Agency will distribute the data after receiving and processing the signals. It will also build a radiometer for gathering data on the rain above the ocean, water vapour content in the atmosphere and liquid water in clouds etc. CNES will develop an instrument for making a vertical humidity profile in the atmosphere and another for providing data on the Earth's radiation budget.

Prior to Megha-Trophique, ISRO will launch Oceansat-2. It will have a microwave radar for measuring the ocean surface wind velocity.

Even as the probes are being planned, recent data have revealed the remarkable self-cleaning capacity of the atmosphere. Every year, about half a billion tonnes of methane and 2.5 billion tonnes of carbon dioxide are removed from the troposphere (which extends up to 16 km above the equator) by chemical reaction. But about seven billion tonnes of carbon dioxide is pushed into the atmosphere annually. Of this, 5.5 billion tonnes are attributed to the burning of fossil fuels (thanks to the proliferating individual means of transport in the absence of efficient mass transit systems in most countries) and a billion tonnes to deforestation, mainly in developing countries. What is noteworthy is one-fourth of the world's population, mostly in the developed countries, accounts for about 70 per cent of the carbon dioxide produced. And since the Industrial Revolution in the West, the level of carbon dioxide in the atmosphere has increased by as much as 25 per cent. Still, the developed countries hesitate to share the burden of remedial measures on an equitable basis.

The oceans can act as a sink to a large extent to absorb carbon dioxide. While several studies are under way, a surprise discovery has puzzled scientists. Microbes, called anammox bacteria, have been found to be consuming carbon dioxide, while releasing nitrogen into the atmosphere.

Cartosat Imagery

The country's first satellite devoted to cartography, Cartosat-1, was launched successfully in May 2005 from the newly constructed second launch pad in Sriharikota. The satellite would be useful in producing better maps of the country's natural resources.

Cartosat-1 has several novel features: two cameras with a resolution of 2.5 metres. It means that it would image from space an object on the ground with a dimension of 2.5 m. Moreover, one of the cameras is mounted in the front portion of the satellite with a tilt of plus 25 degrees (for taking pictures of an object ahead of it along the track) and the other is aft-mounted with a tilt of minus 5 degrees. Data from both cameras would result in stereoscopic images in 3-D with a vertical resolution of four metres. As the satellite traces a circular orbit around the Earth at a height of 617 km, it is designed to revisit the same area every five days. As it goes along, near simultaneous imaging would be possible. The cameras can be steered by plus or minus 26 degrees. This high-resolution, along-track, stereo imaging capacity in a remote sensing satellite is rated as the first-ever in the world.

Cartosat is meant for updating the country's topo maps and also generate large-scale (1:10,000) maps. The image data taken by the satellite are downloaded and processed by the National Remote Sensing Agency.

The satellite acquires the image in what is known as the panchromatic mode (black and white images combining all the frequencies of the visible spectrum). However, the image data are affected by distortions of the platform, which carries the camera and the nature of the terrain itself. This results in terrain displacements, which can be of the order of hundreds of metres. For example, if the elevation angle is 60 degrees, it can show a 600m displacement of the terrain. The distortion is removed by using what is called the digital elevation/terrain model. The models are digital files consisting of points of elevation, sampled systematically at equally spaced intervals.

Key to this exercise is a map of reference points accurately marked on the ground. The points have been selected with the help of global positioning satellites (GPS). About 4,500 points have been identified across the country, following ground surveys and verification. Cartosat imageries will be framed in terms of this reference map. The satellite, which would image 30 km a day, can cover the entire country in about 100 days. In a year, Cartosat can map the entire world. Once corrected and referenced, the maps of the terrain will be more accurate than aerial maps.

With a better knowledge of the attributes of the Earth features now being made available on a commercial basis, applications of the data are increasing worldwide. The value of the imageries will go up, once the mapping data are 'superimposed' on them.

Cartosat-2 (2007) is designed to have a panchromatic camera that can image at less than one metre in spatial resolution with a swath of 9.6 km. It can steer the camera up to 45 degrees from a sunsynchronous orbit of 630 km with a

revisit time of four days, which can be reduced to one day with suitable orbit adjustments. An additional 11m antenna has been installed in Lucknow for Cartosat-2 data reception.

CARTOSAT-2 is capable of providing scene-specific spot imagery. The data from the satellite will be used for detailed mapping and other cartographic applications at cadastral level, urban and rural infrastructure development and management, as well as applications in Land Information System and Geographical Information System (GIS).

With six remote sensing satellites in orbit at the same time (Oceansat, two Cartosats, IRS-1D, Resourcesat-1 and Technology Experiment Satellite) India has the largest constellation of such satellites in the world. Several noteworthy features have been introduced into the system: indigenous data compression, advanced data recorders on board, light - weight mirrors and improved control, monitoring and tracking systems. The sensors carried by the satellites provide a wide range of spatial, spectral and temporal resolutions. The data products are in demand all over the world.

Space Commands from Bangalore

A satellite typically passes over India in about seven minutes. In fact, a satellite is watched for a total of about 35 minutes, as other stations besides Bangalore, are in contact with it from Mauritius, Biak (Indonesia), Bearslake (Russia) and Lucknow. The data gathered from these stations as well as the data collected and stored when the satellite is out of reach of these stations are made available to the ground control in Bangalore. Today, a satellite can certainly be watched in 13 out of 14 orbits a day.

The ISRO Telemetry, Tracking and Command Network Centre (ISTRAC) in Peenya, Banglaore, monitors and controls all low Earth satellites that include IRS-1C and 1-D, P-3, P-4 and P6, used for remote sensing, besides Cartosat-1 and -2 designed for mapping and the Technology Experiment Satellite (TES). They are watched 24 hours a day throughout the year. Teams of specially trained young people keep a vigil and correct the path of the satellites, when needed, under the guidance of experts. ISRO has developed the entire software for the control and display of the health of the satellites.

ISTRAC will also operate the antennae of the Indian Deep Space Network, near Bangalore, set up for the Chandrayaan-1 and other missions.

Typically, a satellite is designed to follow an orbital path within a very narrow corridor. A difference of just 1° in the pointing accuracy at a height of 600 km will result in a difference of 10 km on the ground. The satellite's positioning accuracy, achieved by the Indian team, has improved dramatically over

the years, starting from 0.3° in IRS-1A and - 1B to 0.15° in IRS-1-C, reaching 0.02° in (IRS-P6) Resourcesat-1 launched in 2003. Its path is known within 240 metres of the nominal, mainly because of an innovation called star sensor, which helps determine the path by its orientation with the position of selected stars in the sky.

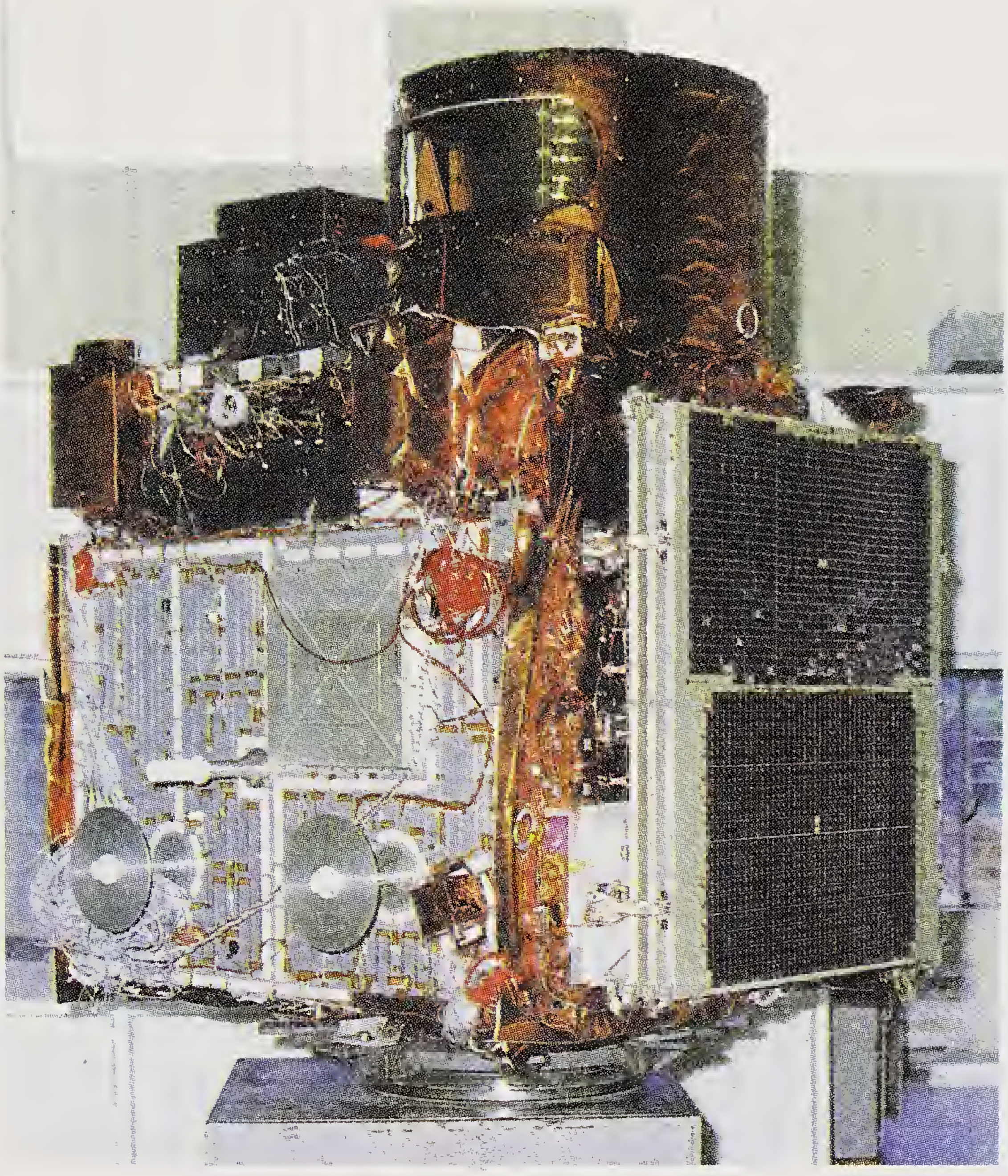
IRS-P6 has another innovation on board, known as Global Positioning System, which ascertains the position of the satellite within 25 metres, as against 80 metres obtained manually from ground-based ranging calculations.

The satellite's health is monitored closely. Its temperature, pressure, the power available in the battery and the solar panels, the status of the gyroscopes and the payload etc. are all registered and compared with the nominal values. One thousand parameters are observed on computers. Any deviation is indicated by a red blinking square on the computer screen. The ground controllers ignore the ones they know are not crucial or permanent, but by force of habit pounce on those that are critical for the success of the satellite. For example, they always check the on-board power level, as the satellite does not see the Sun for 30 minutes in each orbit to get solar power.

If corrective measures do not yield results, satellite component designers are called in to help fix the problem.

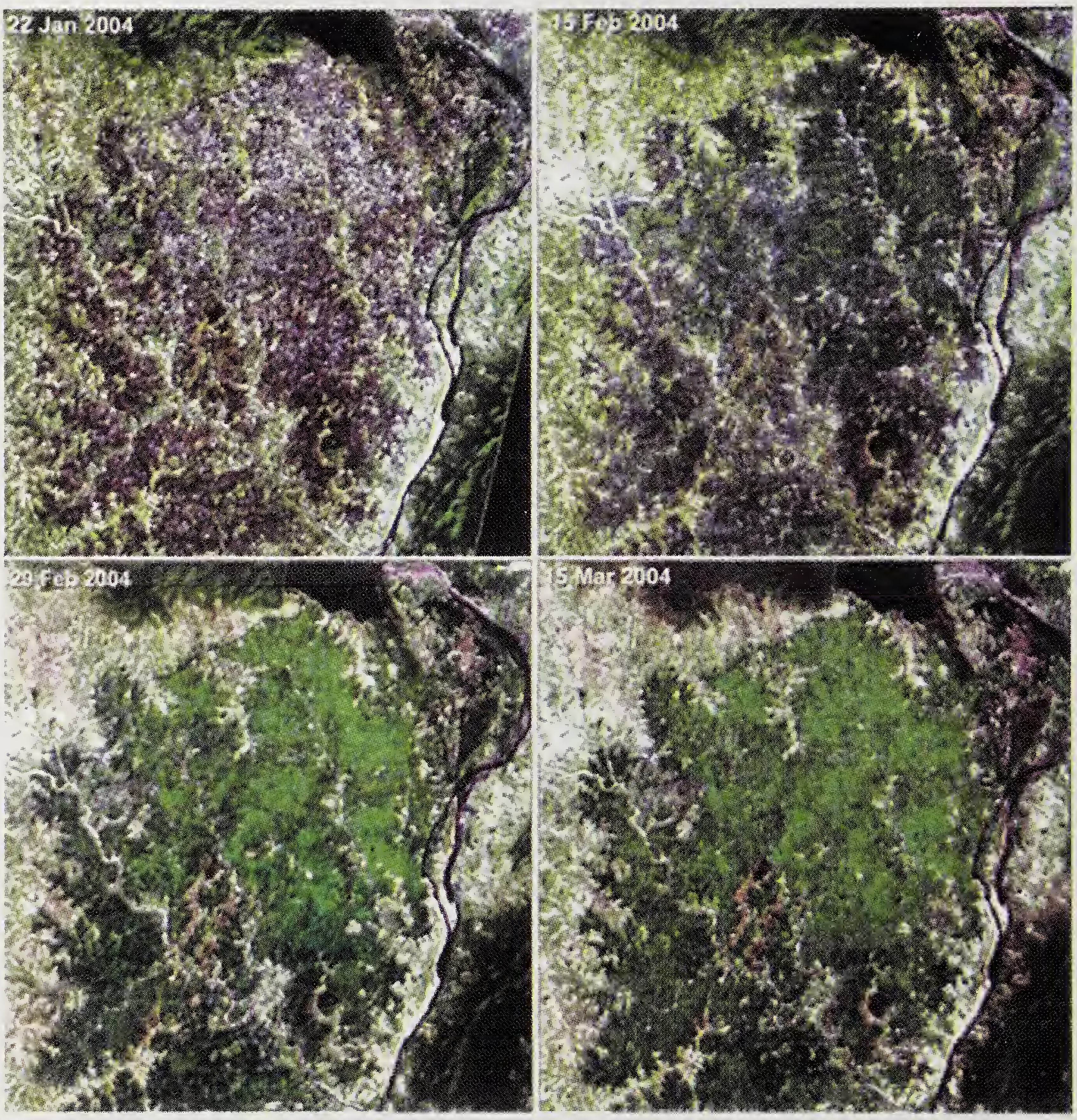
The need for correction arises because of natural causes. Air drag will reduce a satellite's orbital velocity, its altitude and the duration of the orbit. Gravitational forces of the Sun and the Moon will also decrease the inclination of a satellite's orbital plane to the equator. Onboard attitude and orbit control systems counter the disturbances and the satellite is stabilised in all its three axes, viz. pitch (in the up and down direction), roll (along the path of the satellite) and yaw (perpendicular to the other two axes). However, the inclination of the satellite needs correction every six months.

The images sent by the satellites are processed by the National Remote Sensing Agency, Hyderabad. The Agency downloads the data from the satellites, when they pass over it and translates the raw data into images that can be used in a wide range of applications.

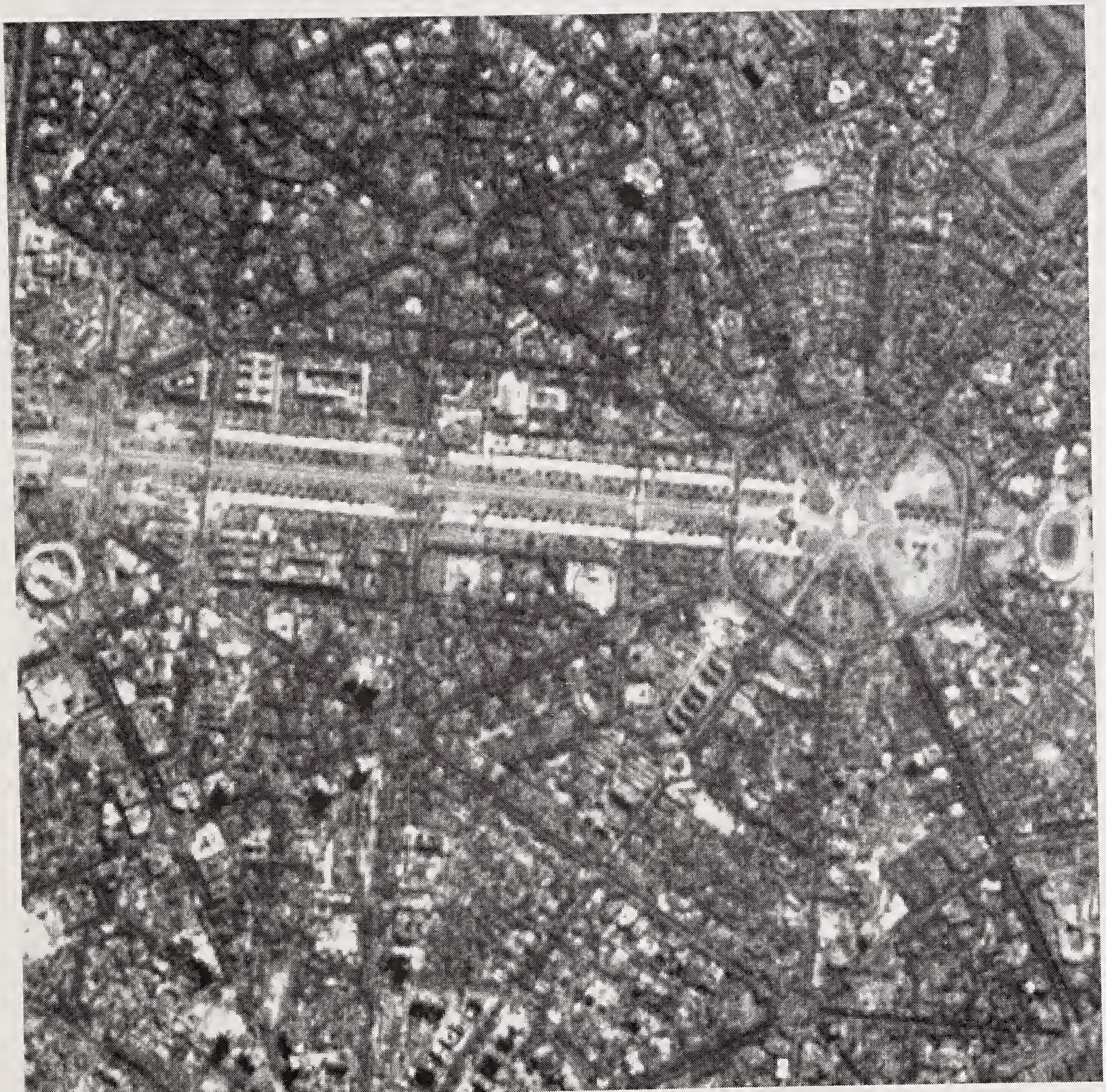


IRS-1C, which has exceeded ten years of operation

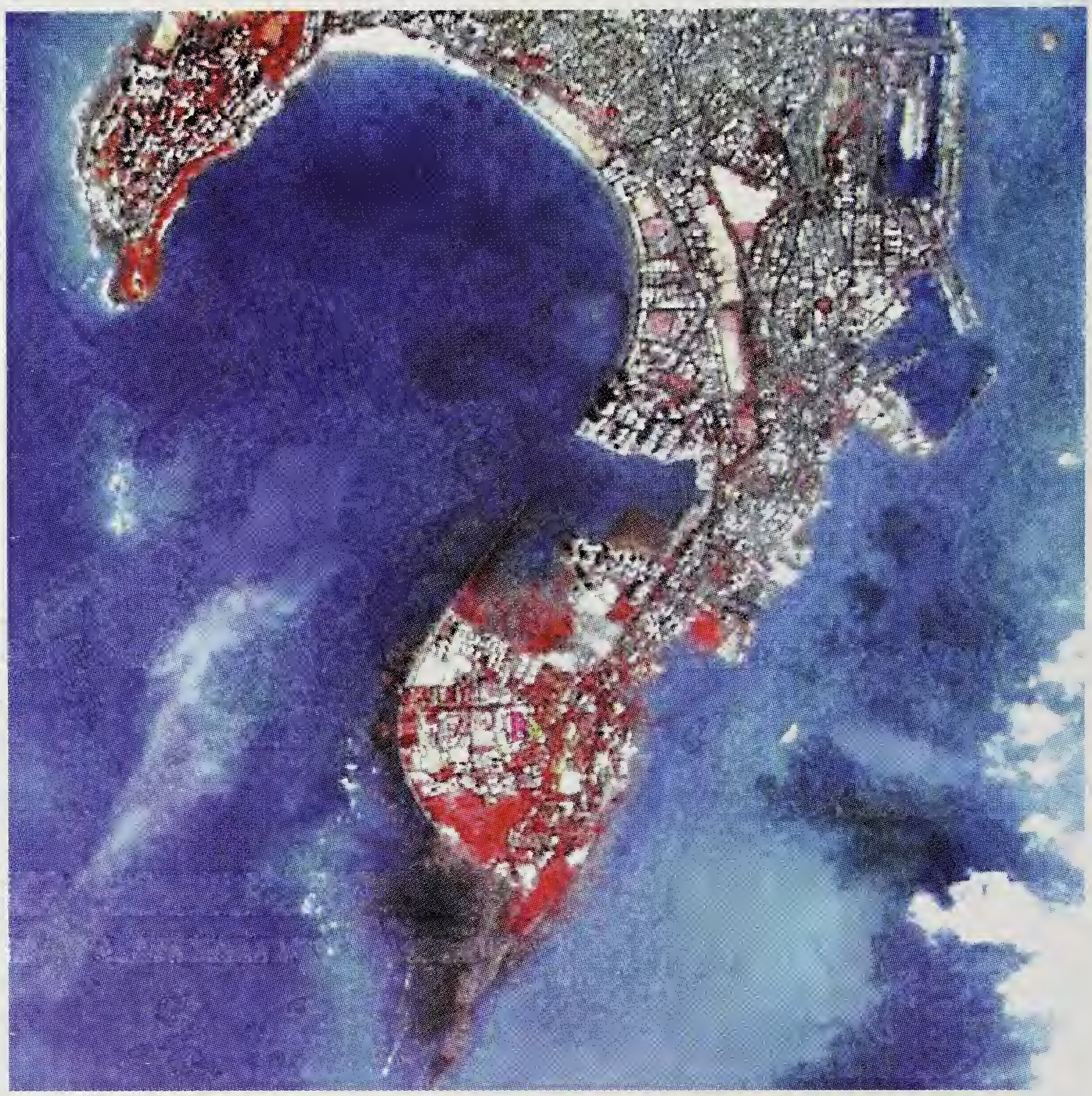
Satellite view of a tsunami-hit area in Nagapattinum



Images of paddy growth in Orissa, taken by Resourcesat-1



New Delhi as seen by a remote sensing satellite

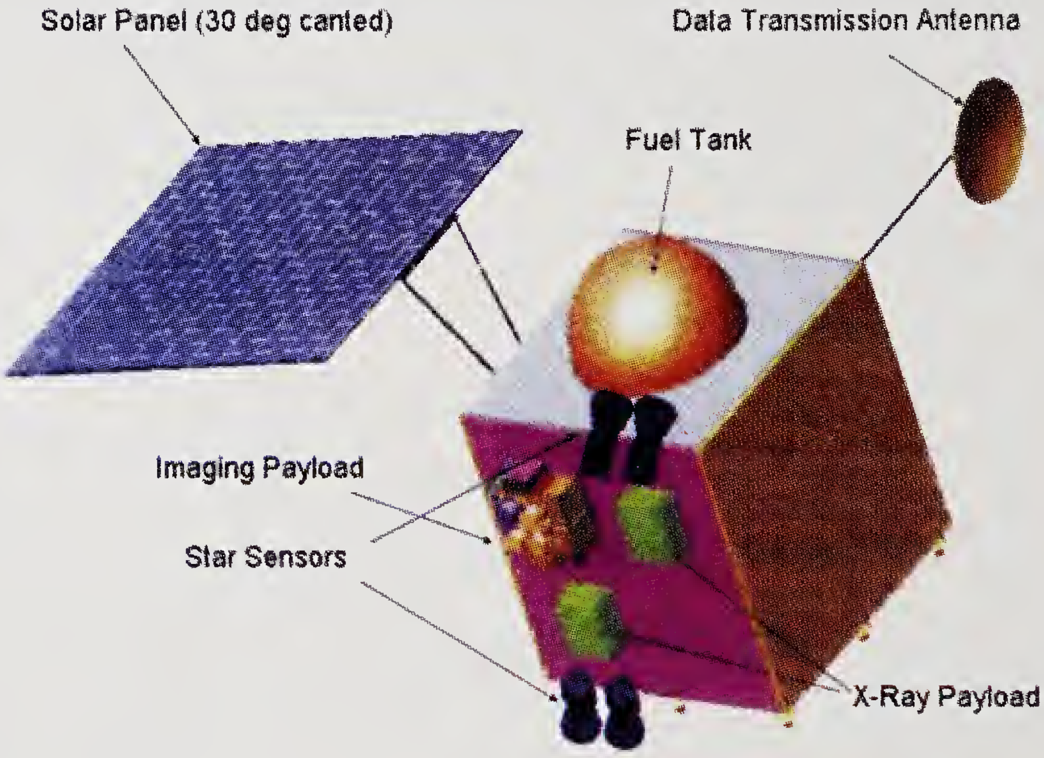


Mumbai from space

Amritsar: as imaged by Cartosat-1

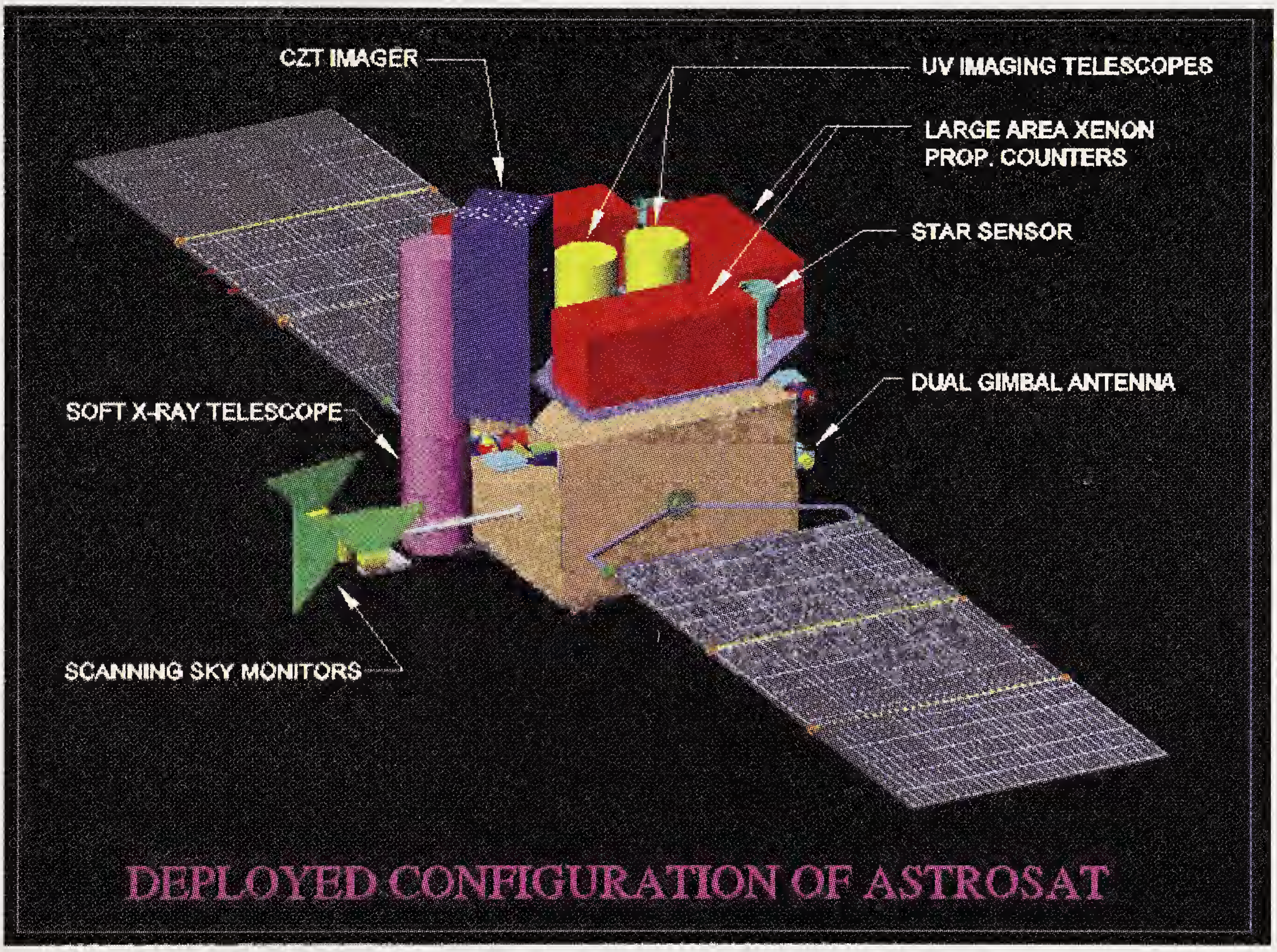
Satellite-aided navigation for civilian use: an artist's impression

Chandrayaan-1:on the way to the Moon



Chandrayaan-1 : the spacecraft

A 32-m ground antenna near Bangalore for the Chandrayaan missions



ASTROSAT: India's astronomy satellite

Cosmonaut Rakesh Sharma (centre)

A BrahMos missile

35. Imaging Sensors

The electromagnetic spectrum is an array of electromagnetic radiations arranged according to frequency and wavelength (Fig 9.9).

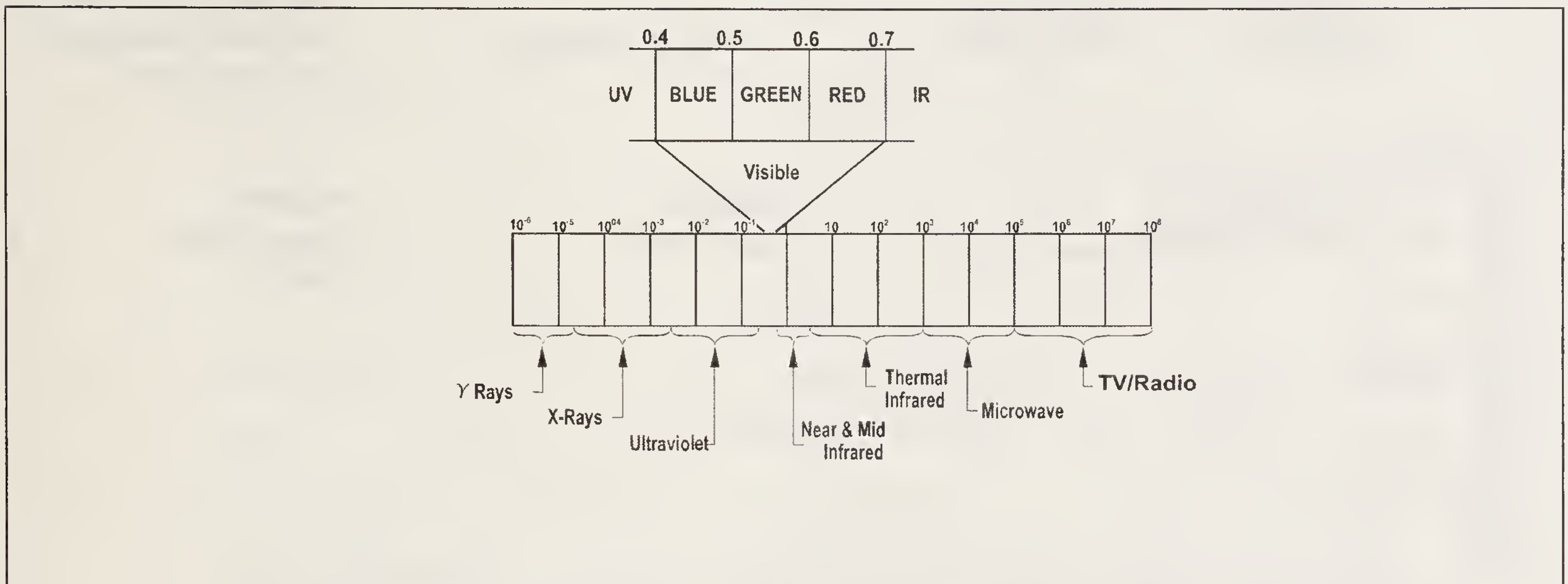


Fig 9.9 : The electromagnetic spectrum: An array of electromagnetic radiations arranged according to frequency and wavelength. The specturm is divided into regions ranging from short gamma rays to long radio waves. The optical window is narrow, ranging from 0.4 micrometer (blue) to 0.7 micrometer (red). Just beyond the red end is the infrared part, which is in turn subdivided to indicate the infrared radiation reflected by the surface, as shown below. Polarisation of the electromagnetic wave is also a useful feature for remote sensing.

The spectrum is divided into regions ranging from short gamma rays to long radio waves. The optical window is narrow, ranging from 0.4 micrometre (blue) to 0.7 micrometre (red). An electromagnetic wave can be characterised not only by its frequency and wavelength but also by its direction of travel and polarisation. The direction of the electric and magnetic fields of an electromagnetic wave is at right angles to each other and both the fields are at right angles to the direction of propagation. The orientation of the fields is shown by polarisation. This is especially useful in scanning the microwave region.

Sensors on board polar sunsynchronous satellites capture the images of the ground in selected bands in the electromagnetic spectrum (Fig 9.10).

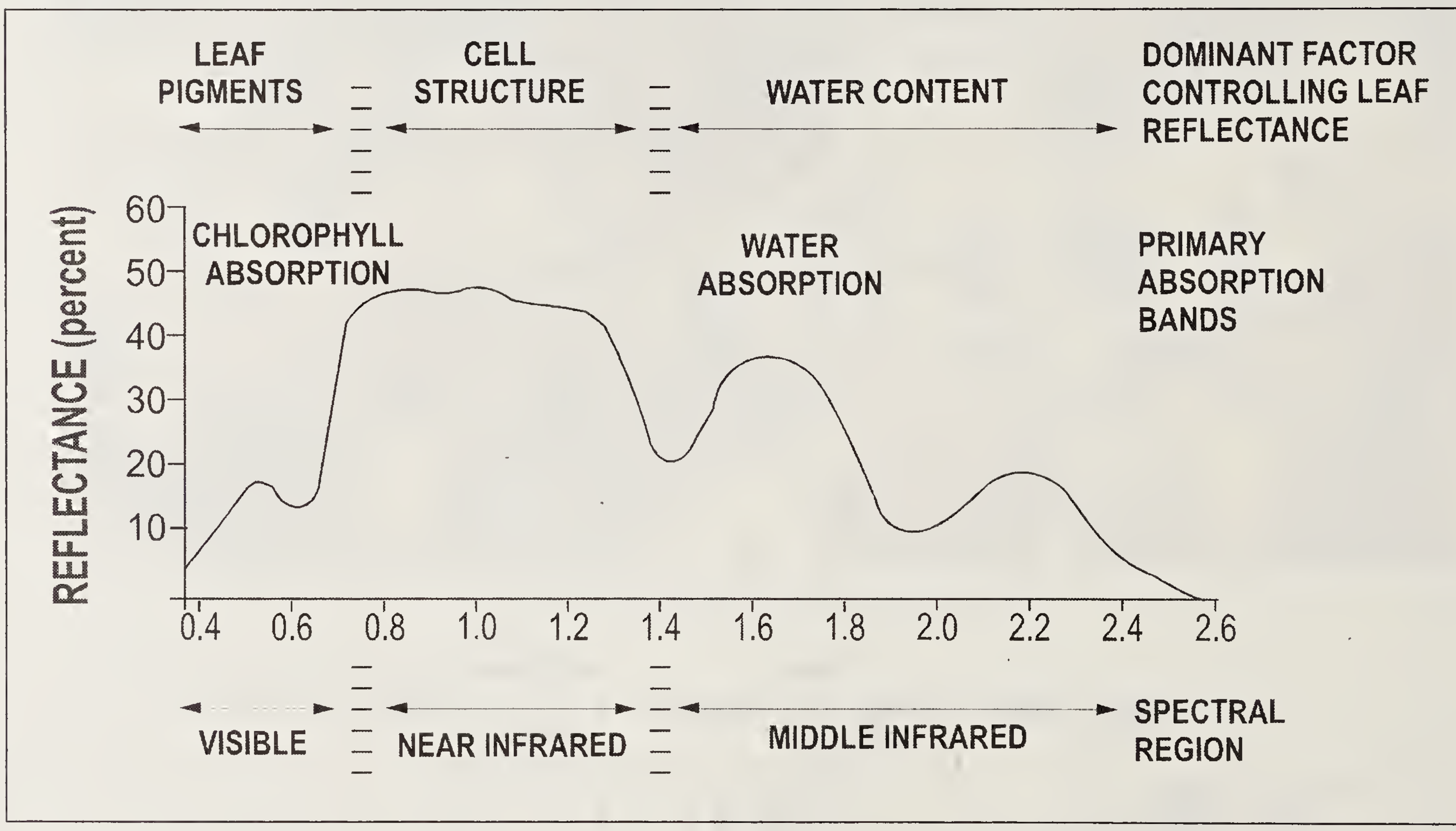


Fig 9.10 : Identifying a crop cover by remote sensing on the basis of the spectral response curve of plants. Leaf reflectance is controlled by its pigments, cell structure and water content. Chlorophyll and leaf water absorb and reduce the reflectance in the visible and middle infrared portions of the electromagnetic spectrum, while the leaf and canopy geometry sharply increase in reflectance in the near infrared region. The spectral response is affected by differences in crop species, by the sun elevation as well as stress and growth factors.

The visible part of the spectrum has wavelengths ranging from 0.4 micrometre (blue) to 0.7 micrometre (red). Adjoining it is the near-infrared region, usually between 0.7 micrometre and about 1.3 micrometre. The wavelengths in the 1.3 – 3 micrometres are known as middle infrared or shotwave infrared. There is also another window called far-infrared between 7 and 15 micrometres.

The near-infrared region is sensitive to properties of vegetation. The region is useful for geological applications. The far infrared is used to determine the temperature of objects such as water bodies.

Microwaves naturally emitted by land (e.g. soil moisture) and sea can be detected by passive radiometers (at 19, 21, 22, and 31 GHz). In the active mode,

radar pulses can be sent and their return measured. The frequencies used for satellite radars range from 5 GHz to 15 GHz.

The spectral bands of IRS satellites are chosen keeping in view their respective study targets. (see Table and Box below).

Table : Spectral Bands and their Applications

BAND	SPECTRAL RANGE (micrometres)	STUDY AREAS
1.	0.45-0.52 (blue)	- Coastal morphology and sedimentation - Soil/vegetation differentiation
2.	(0.52-0.59) (green)	- Vegetation vigour - Rock/soil discrimination on the basis of their iron content. - Turbidity and bathymetry (upto 20 m depth)
3.	0.62-0.68 (red)	- Strong chlrophyll absorption, thereby showing different plant species
4.	0.77-0.86 (near infrared)	- Demarcation of land/water boundaries - Land forms and geomorphology - Green biomass estimation and crop vigour studies
5.	1.55-1.70 (short wave infrared or SWIR)	- Discrimination of crop types, canopy water status, forest type Separation and damage assessment, snow-cloud discrimination
6.	0.50-0.75 (panchromatic)	- Mapping of geological and geomorphological features - Urban planning and urban transportation

Choice of Spectral Bands

The blue region of the spectrum is avoided, since scattering of the signal is more for shorter wavelengths than for others. Hence the bands chosen lie in the green, red, near infrared and middle infrared regions. Vegetation reflects differently in different bands. The spectral response curve of vegetation shows absorption in the blue region, a first

Contd...

peak reflectance at 0.55 micrometres and a low at about 0.67-1.3 micrometres. Again there is a decrease in reflectance (due to absorption by plant water) in the middle infrared region (1.3-2.5 micrometres).

Band 2 (0.52-0.59 micrometres) is centered around the first peak of the vegetation reflectance. Along with the red and near infrared regions, the band is useful for discrimination of vegetation. Band 3 (0.62-0.68 micrometres) provides strong correlation between spectral reflectance and chlorophyll content. Along with band 4 (near infrared) (0.77-0.86 micrometres), band 3 is useful for deriving a vegetation index for studying crop vigour and biomass. There is high reflectance from healthy vegetation.

Band 5 (1.55-1.7 micrometres) in the middle infrared region is ideal for monitoring plant canopy and water status. Band combinations including this band improve the accuracy of crop classification. Snow-cloud discrimination is also possible because frequencies in this band are absorbed by snow and scattered by clouds.

Bands 3 and 4 are used in another sensor, wide field sensor (WIFS) at a different spatial resolution. The WIFS has a large swath (810 km) and high repetivity (5 days). The data will be useful in the assessment of crop condition, drought monitoring, flood mapping and damage assessment. In the panchromatic region (0.59-0.75 micrometres), the spectral responses from the ground features are averaged over the entire width of the band. This technique is useful for mapping at large scales, particularly in urban planning.

The visible and near infrared remote sensing provides information about the chemical properties of a target. Thermal infrared remote sensing gives information regarding the thermal properties of an object. Microwaves provide information on a target's physical properties.

The experimental remote sensing satellites, Bhaskara 1 and 2 provided a resolution of 1 km in two visible bands. The satellites also carried passive microwave payloads operating at 19.22 and 31 GHz. Following the success of these satellites, the development of operational satellites (IRS-1A and IRS-1B) was approved.

Keeping in view the various types of application, it was decided to make multispectral cameras for getting imageries in four bands and in two resolutions (viz. 72 m and 36 m).

The development of the space and ground systems took six years. Different options were studied. One basic decision was not to have a mechanical scanning mirror but to have a charge-coupled device (CCD)-based array.

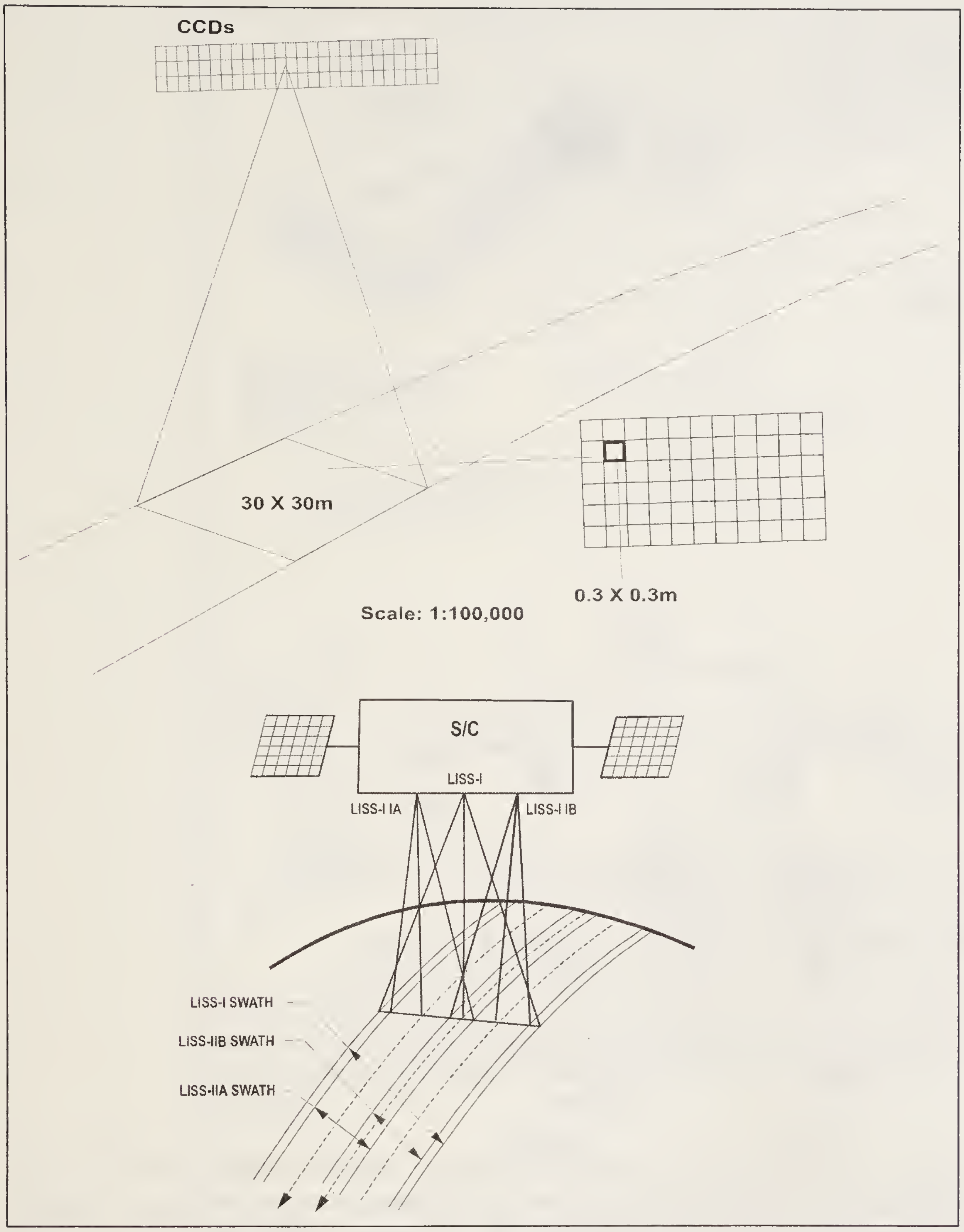


Fig 9.11 : Pushbroom Scan Technique: The satellite's movement results in successive lines of images in the direction of the scan.

Separate lenses were finalised for different bands. CCDs facilitated the adoption of the push-broom technique, by which images were taken as the satellite moves over the target (Fig 9.11).

Both low and medium range cameras were developed using a 2,000 element CCD and what is known as refractive optics for all bands. Getting the specified image quality and the proper calibration proved to be a major challenge. The highly stable platform needed for the satellite involved indigenous development of many new subsystems.

The work involved the development of a three-axis control system using three reaction wheels for controlling all the three axes, sensors for detecting the errors in the direction of the axes and thrusters for the control of attitude and orbit.

Technologically, the new developments include solar-panel fabrication, solar panel deployment and tracking, with the power system handling about 800 watts of generated power. The telemetry, telecommand and tracking (TTC) system had to be newly developed as it was designed to work in the S-band, unlike the earlier satellites (such as Aryabhata, Bhaskara and APPLE) which used VHF for TTC.

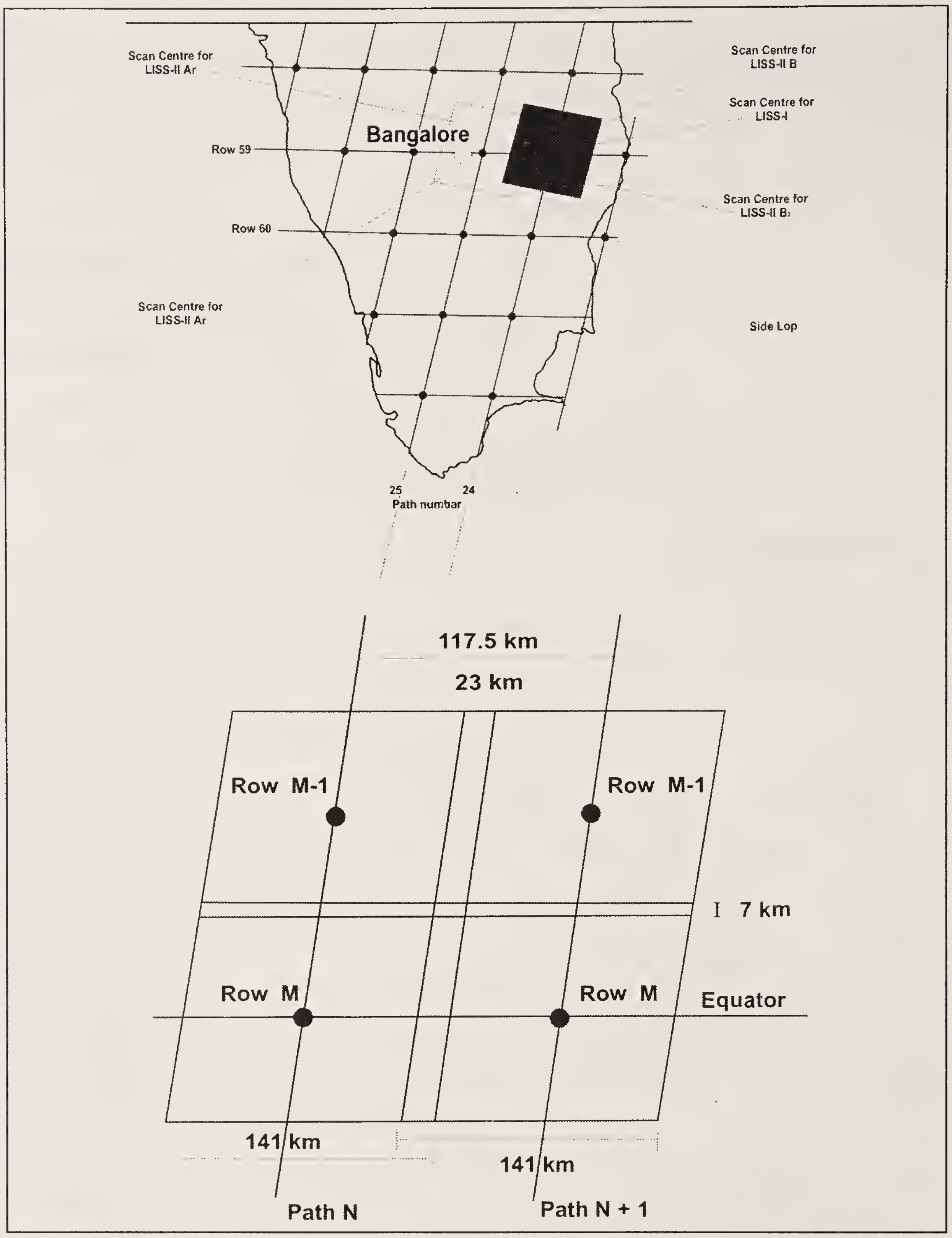


Fig 9.12 : The National Remote Sensing Agency, Hyderabad, receives and processes the images of IRS and other satellites. The referencing scheme for presenting the images consists of paths (north-south lines) and rows (east-west lines). The LISS-III camera captures data in the form of continuous scanlines with a ground swath of 141 km across the track. The data re segmented to obtain a ground coverage of 141 km x 141 km area. The sidelap between the LISS-III scenes in adjacent paths is 23 km at the equator.

Again, unlike Bhaskara, where the data-handling systems were designed in terms of kilobits, the IRS system works up to 84 megabits per second (Mbps). Moreover, IRS, which was designed to weigh 1,000 kg, had to be structurally sound to withstand temperature variations and vibration.

IRS Data Acquisition and Recording

The National Remote Sensing Agency's Shadnagar station near Hyderabad can receive data from Indian and foreign spacecraft (in both S-band and X-bands) and process them (Fig 9.12). The data are recorded on high-density digital tapes.

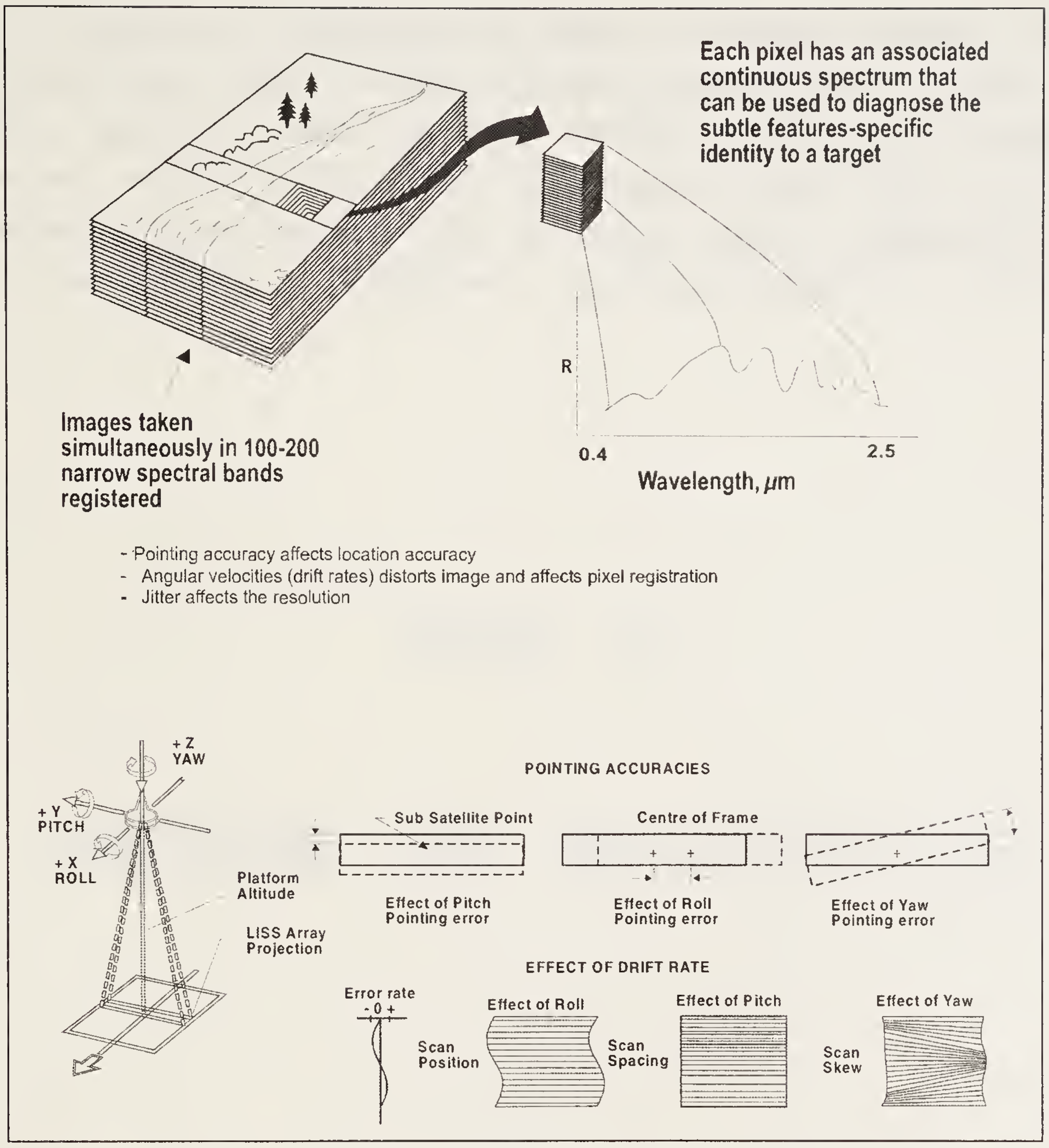


Fig 9.13 : Hyper-spectral images of the Earth's resources are scanned in various frequencies and stored in a user-friendly manner in computers. The sensors on board the resource satellites call for very high pointing accuracies to get distortion-free images.

The NRSA Data Centre generates data products, both digital and photographic. Digital products are available in floppy, cartridge or computer-compatible tapes. The real-time system also provides pass predictions and antenna look angles, scene framing information, automatic cloud cover estimates and data on payload health. Other functions carried out are production of 70 mm quick-look films and computation of error in data. The software for generating standard products such as computer-compatible tapes facilitates corrections of the raw data for the following deviations:

- Sensor-related distortions: Line and pixel drop-out, detector failure or degradation,
- Scene-related distortions due to Earth rotation and curvature etc., and
- Platform-related distortions: attitude variation, altitude variation and velocity variation (Fig 9.13).

Besides standard products, which are generated according to the request from users, browse products are routinely generated after radiometric correction. Satellite imagery is generally available scene by scene according to the specified sensor, path, row and date of pass. The NRSA Data Centre has acquired the capability of providing a single mosaic of all cloud-free imagery recently received for a given area of interest such as a watershed, a district or a State.

PART - X

WATCH ON RESOURCES

36. India Rediscovered

Remote sensing satellites have "rediscovered" India! No longer can one assume that the country's natural resources are in good shape. The state of the land, forests, water sources, dams and canals and environmental pollution, often reveal a disturbing picture, not readily visible to the naked eye. Even as the satellites reveal the dimensions of the erosion of natural resources, the data gathered offer the basis for remedial action. The satellite data also enable planners to monitor the remedial measures like land reclamation and constructive works. The rediscovery of India is one of the most significant benefits of the Space Age.

Nowhere else have remote sensing data made a crucial difference as in the field of agriculture and irrigation. Remote sensing data are used for crop acreage and production estimate ahead of the harvest. A countrywide project covers principal crops like wheat, rice, sorghum, cotton, mustard and groundnut. The area under wheat for the country in the rabi season was estimated at 26.46 million hectares, with a production of 71.55 million tones (2005-06). The area under rice in the khariff season is estimated at 36.41 million ha and the production at 72.87 million tonnes (2006-07). The potato area in the country has been estimated at 1.09 million ha with a production of 22.59 million tones (2006-07). The distribution of cotton crop is also being determined. A geo-referenced cadastral database is being set up to evaluate the accuracy of the data. An improved scheme is envisaged, known as FASAL, which stands for Forecasting Agricultural Output through Agrometeorological and Land-based observations. The scheme has begun in Orissa.

Related to foodgrain output is the extent of wasteland or rather wasted land that can be revived. Over 20 million hectares of wasteland in different parts of the country have been identified. New areas that come under wasteland category as well as those that are reclaimed, are identified. A Wasteland Inventory and Information System, based on geospatial data on 1: 50,000 scale is being designed for display on the Internet.

Sedimentation of reservoirs is posing a big problem. Even if the water level shows full, the sediments reduce the water-holding capacity. A survey of reservoirs in Andhra Pradesh and Maharashtra shows the value of remote sensing.

The extent of water logging and salinity in major and medium command areas has been mapped from space at the request of the Central Water Commission on a scale of 1:50,000. Combined with soil analysis, the satellite data would indicate the severity of salt-affected areas. A database on this aspect is under construction. The aim is to know the status of more than 1,600 irrigation commands in various States. The scheme has proved the use of high-resolution data for monitoring ongoing irrigation projects. All the 140 irrigation projects across India are being assessed for their irrigation potential using Cartosat-1 data.

Two pilot projects in the Upper Krishna project command area in Karnataka and the Teesta barrage command area in West Bengal have been completed with promising results. As an additional application, the new irrigation potential under the Central Loan Assistance programme could be determined.

Watersheds play a key role in ensuring water to dams. Protection of watersheds involves people's participation at the grass root level. Socio-economic data and the physical data need to be integrated. In this respect, the Watershed Development project in Karnataka (known as Sujala), aided by the World Bank, is a success story. Over 850 micro watersheds were taken up in five districts for development. People-oriented data and maps at the cadastral level were used in making realistic action plans. The feedback shows good results in terms of crop yield, crop diversity and household income. Watershed prioritization projects have since been taken up in Maharashtra, Chhattisgarh and Orissa.

The cropping pattern and a crop rotation map for five States in the Indo-Gangetic Plain have been taken up, based on satellite data. The long-term effects of cropping systems on land have been validated for all major cropping systems in Punjab with the assistance of the State Agriculture University in Ludhiana. In Himachal Pradesh, mapping of apple orchards has been taken up.

Under the Rajiv Gandhi National Drinking Water Mission, mapping for groundwater prospects was completed in six States (Andhra Pradesh, Karnataka, Kerala, Madhya Pradesh, Chhattisgarh and Rajasthan) on a 1:50,000 scale for a digital database. The feedback for targeting drinking water has been positive. More than two lakh wells have been drilled and the success rate is 90 per cent. About 7,000 recharge structures have been set up. The Mission is being extended to the rest of the country starting with Jharkhand, Himachal Pradesh and Orissa.

With the operation of Oceansat-1, forecasting for potential fishery zones based on chlorophyll and sea-surface temperature data has improved. Data on sea-surface wind, which will indicate the effects of currents on feeding grounds, have been incorporated into the forecasting. The reliability of the forecast is estimated at 70 to 80 per cent. Forecasting species-specific areas is being developed. A Centre for Ocean Information Services has been set up.

A coastal zone information system is under development using satellite data on selected mangroves and coastal coral reefs, mapped and monitored for the purpose. The tsunami-hit areas of Tamil Nadu and other areas were mapped for planning rehabilitation.

A Disaster Management Support system is being developed with communication and remote sensing satellites. A digital database is being constructed for contour data in hazard-prone areas, using airborne Laser Terrain Mapper.

With a view to be in touch with disaster-hit areas, a satellite link is operational through a VSAT, connecting the National Emergency Operations Centre in the Central government.

Under the Indian Ocean Tsunami Warning System of the Department of Ocean Development, ISRO is involved in establishing a network of seismic stations, tide gauges and data from the unmanned buoys floating in the sea.

IRS satellites play a key role in detecting forest fires, landslides and earthquake-hit areas in time.

Remote sensing satellites are useful in times of flood as well as drought. All flood-hit events in the country are monitored and inundation maps prepared in near real time. Crop conditions are monitored on a monthly basis for possible drought conditions in the States at the district level under the National Agriculture Drought Assessment Monitoring System.

Another significant application is the construction of a Biodiversity Information System. Four main biodiversity-rich areas have been taken up in the first round: the Western Himalayas, North-eastern region, Western Ghats and Andaman and Nicobar Islands. As part of the results, it has been disclosed that as many as 300 medicinally important species have been identified. More areas are being covered: the Deccan Peninsula, the Gangetic Plains, North-west India the Himalayan cold deserts and Lakshadweep.

With the advent of Cartosats, stereoscopic data on land can be had. Spatial resolution maps (2.5 m) are prepared for selected areas; large-scale mapping on 1:10,000 scale has begun. In a significant beginning, cadastral referencing database at the village level has been taken up based on the data from Cartosat in Karnataka and Gujarat.

Using Resourcesat-1, selected parts of the country in both cold and hot desert areas are mapped on the 1:50,000 scale. Land and water resources utilisation plans have been prepared. This would be useful for development at the block level in districts.

Glaciers are emerging as the first measurable indicators of global warming. The study of snow and glaciers is facilitated by data from the IRS satellites. In

the first week of April every year, forecasts for the season (up to June) are made of the cumulative snowmelt run-off from the Sutlej river basin up to the Bhakra reservoir. The forecasts have been pretty close to reality: 16 lakh cusecs against 15.62 lakh cusecs (2006). Snow-cover monitoring is done every 10 days during the season. A related survey has detected a retreat of glaciers since 1962. A glacier inventory is being prepared. The retreat of the glaciers has long-term implications for the country. If the trend continues, perhaps because of global warming, perennial rivers like the Ganga and Yamuna may become seasonal.

Satellite imaging can be presented in a variety of ways. Simple black and white pictures will not be adequate. Capturing infrared data is essential. Hence colour infrared films are used. Satellite data can be presented in colour infrared film. Vegetation generally reflects energy in infrared wavelengths not visible to the human eye. Colour infrared film can record this energy because it is sensitised to green, red and near infrared instead of blue, green and red wavelengths of conventional colour films; on this film healthy vegetation is shown in bright red or pink, and dead or dying vegetation is given a shade of green. This is also called false color infrared technique, in which the colours are shifted towards the longer wavelengths. In this system, blue is generally dropped. Green is assigned blue, red is shown as green, and near IR is represented as red.

In addition to visible and infrared portions of the electromagnetic spectrum, radar and microwaves also provide valuable data, especially when the study areas are cloud-bound. Radio Detecting and Ranging or RADAR is a sensor which detects and measures microwave signals as they are returned from the surface of the Earth. Passive radars measure the strength of 'normal' radiation, which is always present in the atmosphere. Active radars send out their own signal. Large tropical areas that are almost always covered by clouds were mapped for the first time around 1970 by airborne radar.

At an altitude of 10 km, often used by airplanes, one can get a resolution in terms of metres. More than one band can be had by using different frequencies and polarisations (combinations of vertical and horizontal wave orientations for sending and receiving the signals). Multiple bands are useful in detecting different types of land cover. As airplanes cannot cover large areas on a repetitive basis, satellite would require a large antenna, hundreds of metres long to focus the beam and to get the returning signal. This problem is solved by the synthetic aperture radar (SAR). It simulates a long antenna by processing the signals (Fig 10.1).

ISRO is also developing radar satellites, as the major crop season in the country (khariff) is largely covered by clouds and the present satellites cannot penetrate them. Radar satellites (called RISAT) will have a synthetic aperture radar (SAR) in the C-band, with a spatial resolution of 3—50 m resolution. The SAR has a unique advantage: while the radar's physical length remains the same,

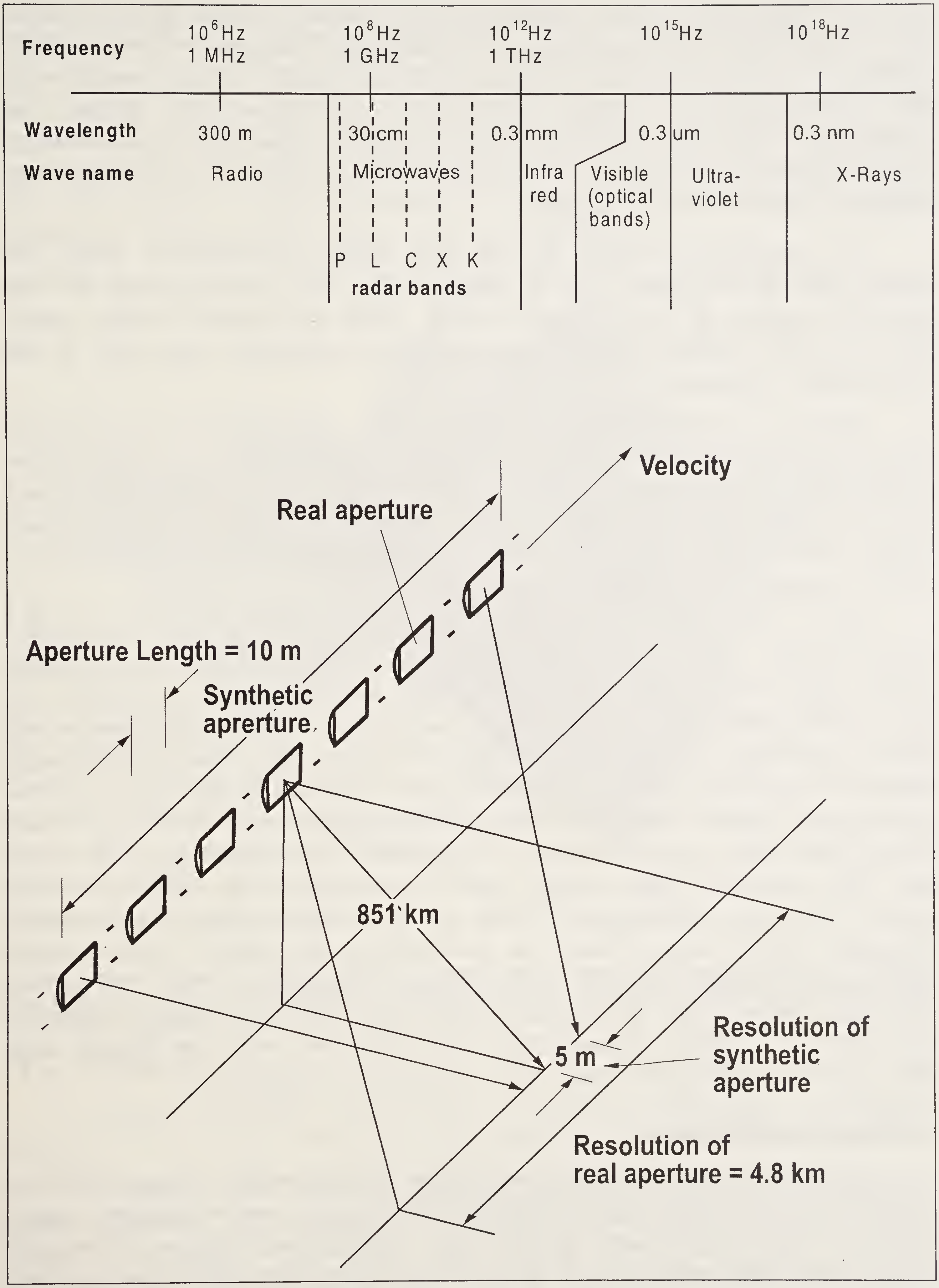


Fig 10.1 : Radar is useful in penetrating the cloud cover that hampers optical sensors. A synthetic aperture radar does not need a physically long antenna for providing better resolution.

its virtual length will increase depending on the distance covered by the satellite. For example, a 10 m long antenna is synthetically enlarged to some 800 m, yielding a resolution of 5 m. A typical SAR will provide 5x5 km images every 200 km along track. A computer processes the return signal. Radar imagery can be combined with the visible and infrared imageries. Apart from crop estimate, disaster management, especially during floods, is expected to be more timely and effective, based on radar imagery.

It is increasingly realised that the best results are possible if visible and infrared data are combined with an imaging radar. This would provide the best from both regions of the spectrum, as radar, which can penetrate clouds, cannot give the clarity available through other windows. Interpreting radar data is still an emerging technique.

There are several advantages in using radar. First, radar uses frequencies that are independent of the weather conditions, such as clouds and haze. Radar provides its own illumination. Second, radar provides unique information on land cover, by measuring the roughness and conductivity of the ground or water surface. Third, radar can be controlled: its frequency/wavelength, look angle, etc., can be changed to meet the requirements.

Some radar sensors are very useful for research on waves and other oceanic studies. But in many cases the waves cannot go through the forest canopy which reflects them away, showing only forest - non-forest separation and not a further differentiation of the forest class. Many forestry applications would require wavelengths capable of penetrating the canopy. The choice of wavelength depends on the type of desired application and is governed by the power available on board the satellite. Radar backscatter strongly depends on the dielectric constant of soils, that relies on the roughness of the terrain and conductivity of the target area. The microwave signal strength varies in accordance with different moisture values. This natural phenomenon is made use of in studies related to soil moisture estimation. NRSA receives radar data and provides the data for various studies such as soil moisture variability under different conditions of crops. Sea surface wind data, derived from the European satellite data, have been used to determine the centre of a tropical cyclone. ERS-1 SAR data have been used together with IRS data for assessing the land cover classification capability.

Looking For Minerals

On the basis of satellite data and airborne information, the Geological Survey of India (GSI) compiles lineament and fault maps, gravity and aeromagnetic maps, as well as seismological and tectonic maps. Satellite-based imagery of selected locations has been enhanced and studied for possible correlation between ground reflectance and mineral presence. The southern peninsular shield, south of 17° N

latitude, encompassing an area of 400,000 sq. km. was studied for minerals under Project Vasundhara. The Regional Remote Sensing Centre, Bangalore, of the Department of Space created the database and developed the GIS for it, while the Airborne Mineral Surveys and Exploration Wing of the GSI collected and synthesised the geo-scientific data. The Indian National GIS (INGIS) developed specifically for the Project is capable of analysing any type of natural resource data. The database is now operational. A method for evaluating the economic viability of mining projects has also been developed.

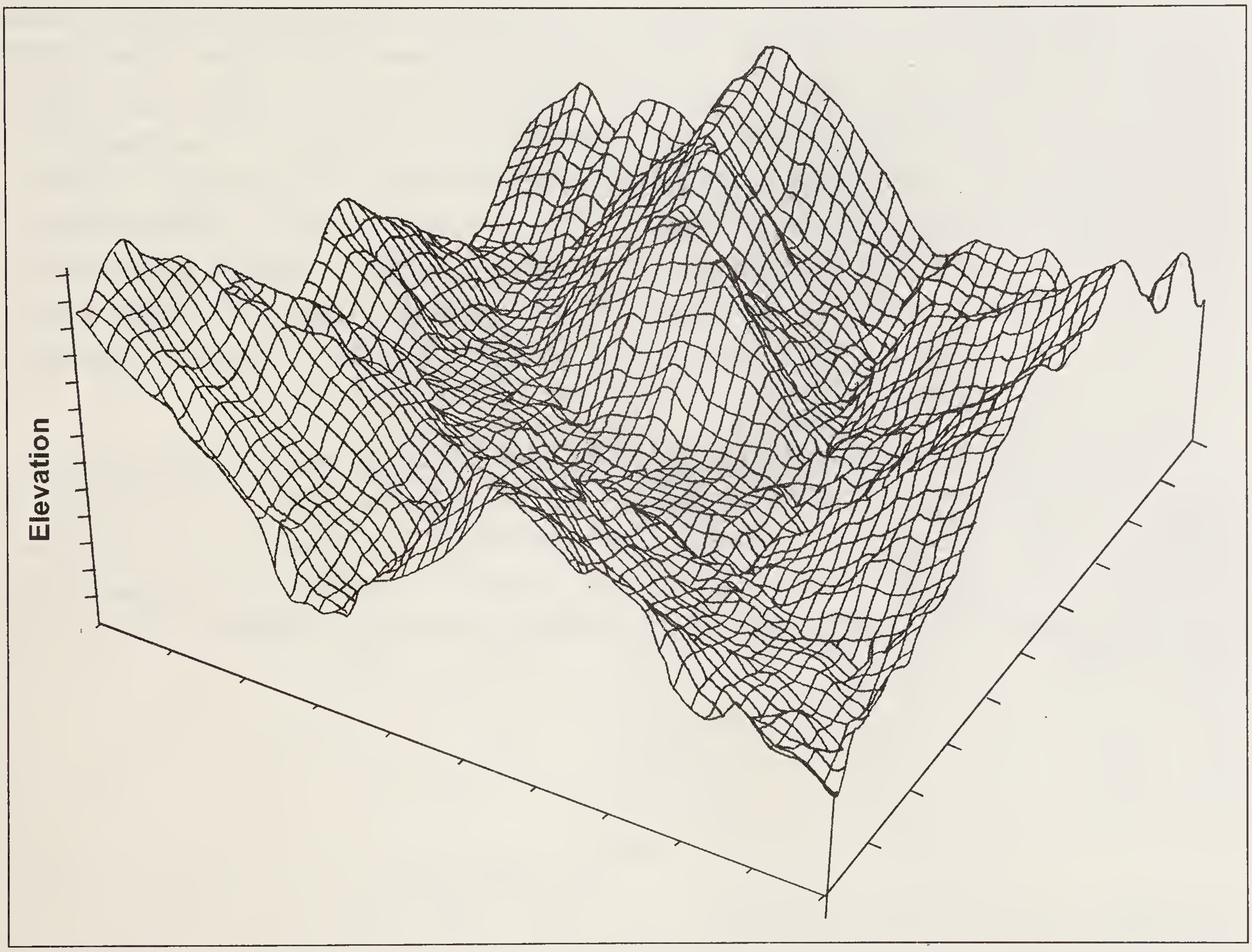


Fig 10.2 : Digital Elevation Models, prepared from satellite-derived data, are useful for a better understanding of a terrain with slopes.

The Challenge

Though considerable progress has been made in using remote sensing data, there are several areas where the data could not be put to effective use.

In regions where mixed cropping is practised, estimating crop production poses difficulties. The information on potential fishing zones, based on satellite data, is now valid for areas more than 10 km offshore and hence not useful to small-scale fishing operations. More accurate payloads on satellites are necessary for improving the data. Remote-sensed data on wastelands have been found at

variance with the surveys made by the Department of Wasteland Development. Efforts to reconcile them have been initiated. Although data on groundwater are available, several States, particularly in the north-east, could not use them for want of well-organised groundwater departments.

Digital elevation models (DEM) are used to correct the distortions induced by the terrain. Getting DEM from map calls for expensive map scanning system, adequate software and training; or the DEMs can be derived from stereo pairs obtained by a space sensor (Fig 10.2).

The combination of high-resolution data along with stereo-viewing is used for the generation of a detailed carto-graphic database. The data from PAN camera can also provide accurate digital elevation models, useful for terrain mapping and production of contour maps. Stereo images at a high re-visit frequency would enable planners to understand population dynamics and do better utilities planning. The LISS-III data, for example, can be effectively used for discrimination of crops in the mixed crop areas and for mapping of various thematic information. A five-day repetivity will be useful in generating growth profiles at almost every stage of a crop. The data from WIFS will facilitate natural resource monitoring at regional and global levels.

Remote sensing techniques are useful in identifying areas for mineral search. Thematic maps are necessary for this work. The maps serve as geological, geophysical and geochemical guides for locating the minerals. A database is created. It is digitized so that it can be used in computers. A methodology is also developed integrating data from several sensors on different themes at various levels.

37. A Resource Database and GIS

Several organisations, besides the National Remote Sensing Agency, carry out remote sensing application projects. The organisations include the regional remote sensing application centres in Bangalore, Dehra Dun, Jodhpur, Kharagpur and Shillong; Space Application Centre, Ahmedabad and State government agencies. Several non-government organisations also participate in the activities.

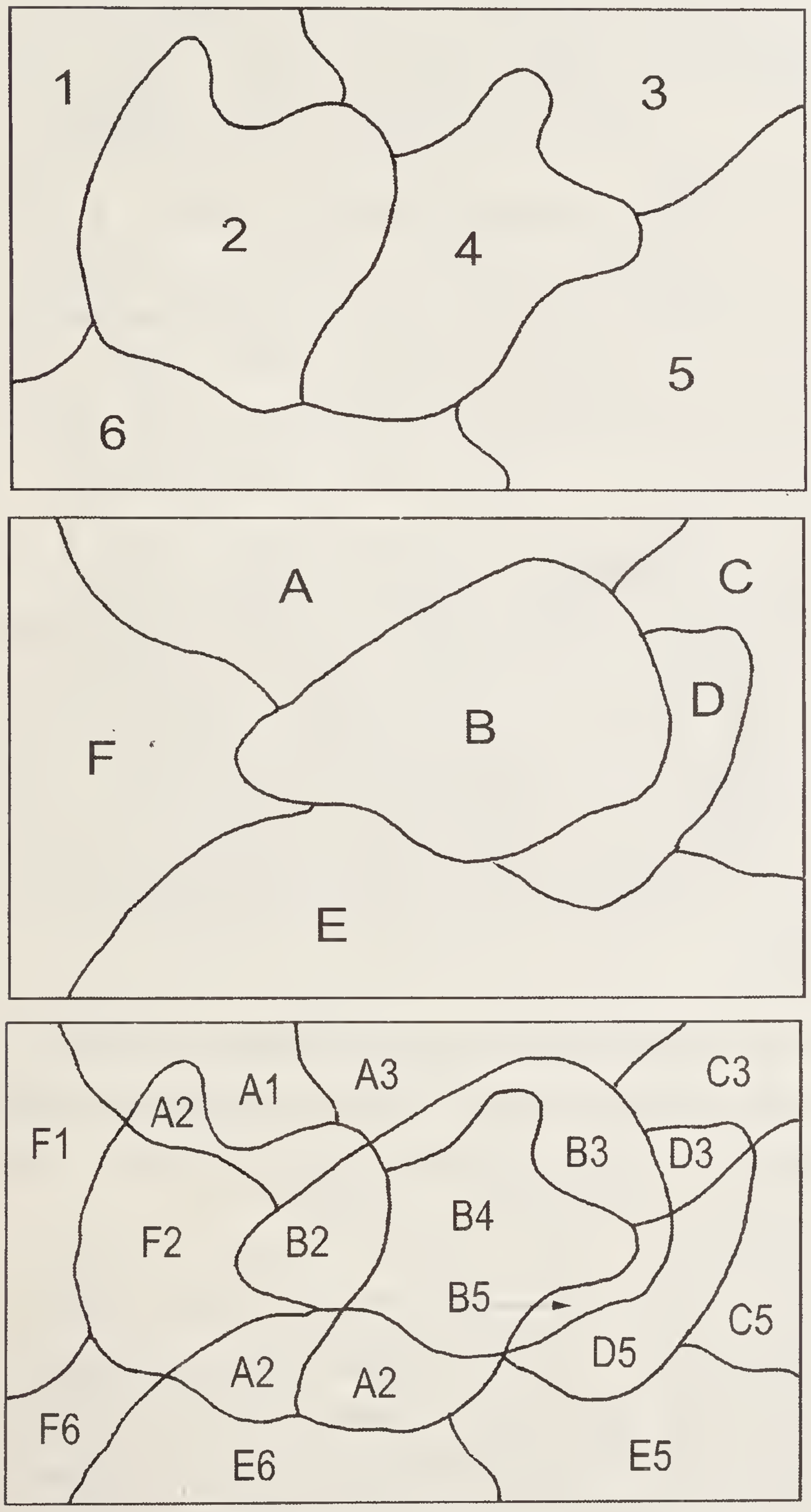


Fig 10.3 : A Geographical Information System (GIS) integrates different maps and data of the same location according to instructions given. In this example, six types of soil (1—6) and as many types of vegetation (A—E) are combined in a new map (bottom) of soil and vegetation for further analysis.

Sustainable development of natural resources involves the preparation of resource maps based on remote sensing data, collection of ground data including the data on the people that may be affected or benefited in a project, and integration of the different types of data.. The integration of the data is done in the geographic information system (GIS). GIS has become essential for planning the use of natural resources.

Basically, GIS refers to a computer-based information storage, processing and retrieval systems for analysing geographically referenced data. Its digital database has several layers of information on land use, land cover, infrastructure and on the people involved (Fig 10.3).

India has made good progress in adopting GIS. With a view to ensuring optimum use of the country's natural resources, a National Natural Resources Management System is in place with the

Department of Space as the nodal agency. An Information System to support it, based on a National Natural Resources Repository, has begun in several States.

Non-computer forms of GIS were commonly used in the early 1980s. It consisted of a series of databases and maps overlaid upon a light table. The process was time-consuming and the end map could not be quickly revised after its production. Differences in scale in the source maps added another problem.

The computer revolution and rapid changes in information technology have turned satellite imagery into a high value-added product. After the images from space are corrected and converted into a digitized format, the data can be integrated with conventional information.

In a computer-based GIS, new maps can be generated precisely and quickly, integrating the data layers according to plan. In this form of GIS, maps are converted into a digital format by tracing them with an electronic cursor (digitizer). It is called automated mapping function by which geographical data (line, point or area) are digitized electronically into a computer database. Once a map is digitized, its alteration into any desired format is possible for analysis. GIS provides the capacity to overlay different maps on the same location. The soil and vegetation maps, for example, can be overlaid and combined into a new map of soil and vegetation.

The data could be specific features of a location (slope, rainfall, soil type, etc.) or attributes such as statistics or text, tables and lists. In GIS, maps are converted into a computer-compatible digital format, and selected information from different types of data are combined and compared. It then becomes possible for the resource planner to study the interrelationship between the various data and get answers to many 'what if' questions. Model building becomes scientific and realistic. The most important feature of GIS is its analytical function. Satellite data are integrated with maps and tabular data.

There is a growing realisation that the natural resource information should be combined for study with socioeconomic information. For instance, data on land use or forests should be seen in the context of demographic data, keeping the focus on people and their problems.

The major applications of data under GIS include: geology, forest density mapping, turbidity levels in reservoirs, crop type discrimination, crop acreage estimation, sand dune migration, delineation of groundwater potential zones, land use, mapping of floods and water bodies, fisheries, drought management, wasteland mapping, environmental impact of mining, etc. Digital image processing systems have been set up at five regional remote sensing service centres. Several software programmes for application in projects have been developed.

A project for large-scale mapping of the country is under way. The objective is to generate a set of cartographic maps on 1:10,000 scale. A programme on natural resources census has been initiated for the entire country. A portal providing information on the NNRMS is on the Internet.

The National Highway Development Project is another major initiative for enhancing the capacity for widening and strengthening high-density corridors totalling over 13,000 km and upgrading another 10,000 km. The Project uses remote sensing and GIS.

Most spatial features can be displayed as points, lines or polygons. A point is a small feature (a city or island) relative to the whole map. Lines are used to represent roads, pipelines boundaries and other linear features. A polygon refers to any area or region and is the basic unit on a thematic map, usually irregular shaped and variable in size.

In a computer system, a regular map is generated using two basic geocoding systems, called vectors and grids. A vector system stores data as coordinates. Each uniform area is surrounded by a set of straight-line segments called vectors. A grid or raster system stores data as a string of characters in which each character represents a location. It is a cell-based system in which a map is represented as an array of rectangular or square cells. In vector-based system, a pair of X and Y coordinates represents every point. An advantage of the vector-based system is that it indicates thematic maps precisely and needs less computer storage space. But satellite imageries cannot be represented as vectors. The raster-based system is necessary and it has several advantages: the processing is simpler and compatible with other digital imageries. The algorithms needed are less complex. However, the storage requirements are larger and the cell size chosen determines the resolution. A raster system (also called a grid) for display of satellite imageries is like a television image composed of picture elements (pixels) which are essentially grid cells. A grid pattern is useful where spatial features like land patterns have to be recognised for comparison and analysis. A grid-based GIS can be easily used in a computer.

A significant application of GIS is the construction of models of the real world based on digital data. Modelling can analyse trends and identify the factors that cause them. What is more, it can indicate alternative paths to solving the problem and spell out the consequences of decisions. For example, a GIS can show how a natural resource can be affected by a decision. Based on satellite data, one can identify areas that suffer most from deforestation and find out the likely impact of any regulatory measures. A GIS can indicate the likely change in quantitative terms of a new area development. GIS can also be used to determine optimal routes for communications, roads and irrigation.

GIS applications are generally grouped under six categories: display of thematic and location data; calculation of area and length of map features; reclassification of thematic attributes of map features; overlay of features along with associated thematic attributes of two or more geographically coincident maps; distance measurement; and comparisons and contiguity indications.

The success of GIS depends on the degree of relevant information. In developing countries, the collection and processing systems are relatively inadequate. The data collection and processing should be improved before GIS is introduced on a big scale. Moreover, in evaluating and interpreting the data, there should be good co-operation between the computer specialist and the subject expert. GIS can in fact enhance the understanding between the generalist decision-makers and technical experts.

Empowering the People

With a view to informing the people at the grass root level and eliciting their views and co-operation, village resource centres (VRC) have been started in several States, linked by the INSAT system.

Some 200 centes are working in Andhra Pradesh, Bihar, Jharkhand, Kerala, Maharashtra, Madhya Pradesh, Orissa, Rajasthan, Tamil Nadu and Uttaranchal. A hundred more are being set up in other States. About 40 NGOs and Trusts are associated with the centres.

Linked to the satellite by a VSAT (Very Small Aperture Terminal), a VRC enables the villagers to have online interaction with local farmers, agriculture scientists and other experts at the district and other levels. Weather conditions, price fluctuations for farm produce, the state of the sea, the height of the waves and a host of information specific to the area and the people are some of the topics discussed. A VRC is a virtual learning centre and also connects to a specialty hospital. Persons at one node can fully interact with those at others through video and audio links. Each one of the nodes can further be expanded by optical fibre (provided by BSNL) and low-cost wireless systems.

The M.S. Swaminathan Research Foundation (MSSRF) implemented the idea of the VRC as a small beginning in 1997 in Pondicherry with the support of the Canadian aid agency. There was no model to follow. But the scheme itself soon became a model. It was planned as a people-centred scheme. It started from the premise that Very Ordinary Persons (VOPs) have a right to know. Accordingly, village vulunteers were trained in the operation of computers and maintenance of the communication equipment and gather information on prices, health care, water management, etc.

Prof M.S. Swaminathan has emphasised that content should be as important as connectivity. It is not enough to provide the connecting links. What is transmitted across is significant. Hence the contents provided by the links are area-specific and timely as far as possible. For the first time, information on many government schemes is available at the village level. It is hoped that every village connected with a VRC would become a knowledge centre, ‘a coalition of all concerned in bridging the digital, technological, economic and gender divide in rural India’. Such a link would help extend the knowledge revolution to all the villages in India on an environmentally sustainable and socially equitable basis.

PART - XI

EXPLORATION

38. Chandrayaan-1 : India's First Moon Mission

Several unmanned and manned Moon missions were conducted in the 1960s and the 1970s. Today there is a worldwide renewed interest in fundamental research on the Moon. Several countries are planning to launch lunar missions not only to study the Moon and the early history of the solar system but also to use the Moon as a platform for further exploration. In India, about a hundred scientists considered the scope for lunar research and proposed an unmanned scientific mission. Following the approval of the proposal in 2003, foreign academics and agencies interested in lunar studie, were invited to participate in the mission by contributing their payloads. Six foreign payloads have been selected to fly with the five designed by ISRO.

The main objective is to have a 3-D atlas of the Moon at 5-10 m spatial resolution, based on the study in visible, near infrared and x-rays. Both the near and far side of the Moon will be covered, and geological, chemical and photo mapping will be done simultaneously. The chemical and mineralogical mapping of the entire surface will be done. Different sensors will look for aluminium, silicon, calcium, iron, titanium and magnesia at a spatial resolution of about 25 km. High atomic number elements such as uranium, thorium and radon will also be mapped (Fig 11.1).

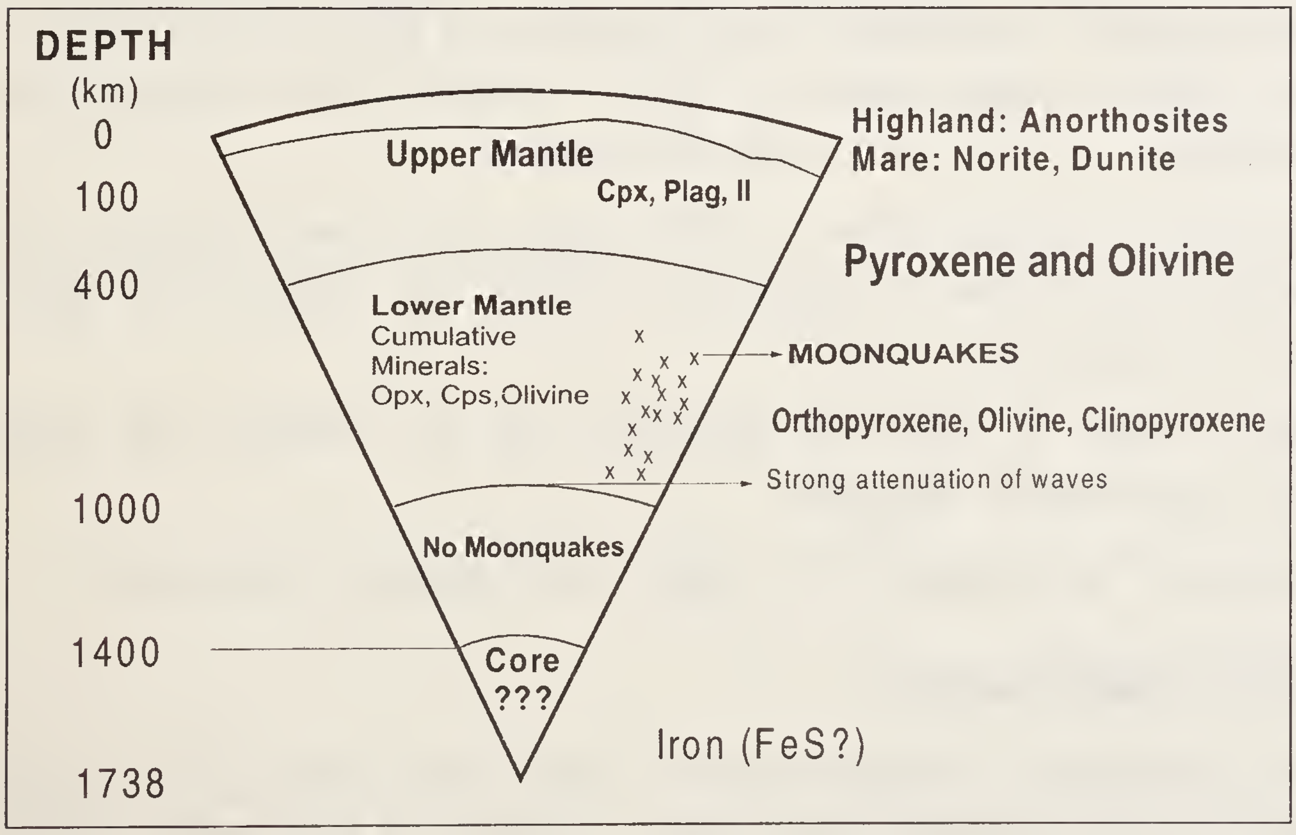


Fig 11.1 : The internal structure of the Moon: an outline.

Chandrayaan-1, will be a cuboid weighing 1304 kg at launch and 590 kg in lunar orbit. It will be three-axis stabilised, guided by two star sensors and four reaction wheels. Its solar

array will produce 700W of peak power and lithium batteries will supply power during its eclipse from the Sun. The science data gathered will be stored on board for which there is 32 GB capacity. A separate storage for mineral data at 10 GB is designed. A special Deep Space Network has been set up at Byalalu, near Bangalore for the mission. It consists of a 18 m and another 32 m antennae managed by ISTRAC.

Chandrayaan-1 will be launched by a PSLV, a rocket, which achieved maiden success in 1994. Subsequent PSLVs had launched several satellites successfully including Kalpana-1, a geosynchronous spacecraft. PSLV has been proven to be a reliable rocket that can function as a GSLV with reduced load.

The Moon mission envisages an initial orbit of 240 km by 24,000 km, followed by a trans-lunar injection orbit and finally after 5½ days lunar orbit injection. In its final circular orbit, it will be 100 km above the Moon (See Back Cover illustration). There are eight 22 N thrusters to keep the spacecraft steady in the right direction. It has a liquid apogee motor of 440 N.

Scientific Payloads

Chandrayaan-1 will carry five Indian and six foreign payloads for scientific analysis. ISRO's payloads and their objectives are as follows:

- Terrain Mapping Stereo Camera: It will map the topography in both near and far side of the Moon and prepare a 3-D lunar atlas.
- Hyper Spectral Imaging Camera: It will collect spectroscopic data for mineralogical mapping of the lunar surface.
- Lunar Laser Ranging Instrument: It will produce an improved model for lunar gravity field by using pulses of light to illuminate the terrain. The density distribution of the crust will be mapped.
- High Energy X-ray Spectrometer: It will study the X-ray emission (in the 30 to 250 keV) due to radioactive decay of uranium-238 and thorium-232 on the lunar surface.
- Moon Impact Probe: It will ride piggyback on the satellite and will impact on a pre-selected location.

The foreign payloads are designed to realise the following objectives:

Chandrayaan-1 X-ray Spectrometer :

It indicates the elemental composition of the lunar surface by x-ray fluorescence. It works on the principle that when a primary X-ray beam strikes

a sample, the x-ray beam is either absorbed or scattered, and a characteristic x-ray emission that follows will indicate the composition of the surface.

A German payload, near-infrared spectrometer, will survey mineral resources and the chemical composition of the crust and mantle, by analysing the sunlight reflected by the Moon. It would indicate future landing sites.

Another payload, organized through the European Space Agency, called Sub keV Atom Reflecting Analyser, is designed to study the particles (mostly low energy neutral atoms) that are scattered by the lunar surface when the solar wind (charged particles) hits the Moon. As the Moon has neither an atmosphere on a magnetosphere, the atoms that escape the lunar surface would indicate the nature of the surface.

A payload designed by the Bulgarian Academy of Sciences will evaluate the Moon's radiation environment and indicate the extent of shielding needed against radiation.

A miniature synthetic radar from the Applied Physics Lab of John Hopkins University and Naval Warfare Center (USA), organised through NASA, will explore the possibility of water on the Moon. As the Moon's axis of rotation is perpendicular to the ecliptic plane, the poles of the Moon are permanently dark, subject to constant bombardment of cometary debris and water-bearing minerals. All permanently shadowed areas will be mapped.

Another payload from the U.S. (Brown University and Jet Propulsion Laboratory), Moon mineralogy mapper, will produce high-resolution mineral compositional maps and improve our understanding of the early evolution of a differentiated planetary body and assessment of lunar resources.

39. India's First Astronomy Mission

Since 2001, scientists have found hard X-rays (above 10 keV), which can be studied from balloons at about 40 km above the earth. Hard X-ray detectors on satellites have unveiled colliding galaxies and hot disks that swirl around black holes. But there is no mission planned for the next four years with broad spectral coverage from 0.3 keV to 100 keV. Hence it would be useful to have a satellite, which can simultaneously study cosmic phenomena in the X-ray, ultraviolet and optical regions in the desired bands.

The Tata Institute of Fundamental Research (TIFR) Mumbai and the Physical Research Laboratory in Ahmedabad have been gaining experience in studying X-ray astronomy through balloons and sounding rockets from the mid-1960s. TIFR and ISRO had gained experience in the design and fabrication of satellite-borne detectors for gamma rays also. The ISRO Satellite Centre designed the gamma ray burst detectors aboard two satellites in the SROSS series, one of which worked for seven years. The X-ray detector on board IRS-P3 also worked for seven years.

Given the expertise and widespread interest in cosmic studies, ISRO and other institutions agreed to design and launch the country's first multi-wavelength astronomy satellite.

A PSLV rocket would launch Astrosat in 2009 into a circular Earth orbit of 600 km with an orbital period of 100 minutes. The science payload will weigh 868 kg out of a total satellite mass of 1608 kg. The satellite is expected to have a minimum lifetime of five years.

Different instruments will detect X-rays in low energy (0.3 – 8 kev) and high energy (2—100 kev), besides simultaneous observations with several detectors.

The state-of-the-art instruments that are used would identify and quantify the nature of the X-ray objects such as X-ray binaries (a bizarre X-ray-emitting star orbiting a stellar corpse called a neutron star). Other phenomena to be studied would include: steady and periodic X-ray glows as well as flaring bursts and transient sources; supernova remnants; cosmic X-ray background and variations in the emission from active galactic nuclei.

Astrosat is a unique satellite with five telescopes covering a broad X-ray region, and ultraviolet and optical bands. It has the largest collecting area for any observatory in space in the X-ray band above 20 keV. The instruments include three Large Area Xenon Proportional Counters (LAXPC). In the 20-80 keV range, Astrosat will have larger than the present largest instruments in space. The cosmic X-ray sources, which will be observed, cover a wide area—from the nearby galactic X-ray binaries to clusters of galaxies that are the largest structures in the universe. The instrument will study neutron stars, black holes and objects that have the highest known magnetic field strength in the universe. Another interesting phenomenon for study would be X-ray pulsars (pulsating stars) lasting barely milliseconds. These are considered the missing link between radio pulsars and low mass X-ray binaries.

The telescope (LAXPC) will work with a cadmium zinc telluride (CZT) detector array, which is a new generation X-ray detector. It will be able to measure the X-ray spectrum with unprecedented accuracy in the 2 to 100 keV energy range.

Another detector is called Soft X-ray Imaging Telescope (SXIT), sensitive to soft X-rays (in the energy range of 0.3 - 8 keV) in the total band of 0.3 - 100 keV. The detector can resolve point sources with an accuracy of an arc minute, equal to $1/60^{th}$ of a degree (an arc second is equal to $1/3{,}600^{th}$ of a degree).

Yet another detector, the Scanning Sky Monitor, is designed by ISAC and the astrophysics group of the Raman Research Institute, Bangalore. The detector is designed to zero in on X-ray sources, which vary by a factor of 100 or more in a few days. X-ray transients, as they are called, may appear any time anywhere in the sky.

The inclusion of an ultra violet detector in Astrosat is timely as all foreign UV satellite probes are nearing the end of their design life. UV is useful in probing a wide range of physical conditions of matter from the very cold gas (30 K) to the hot gas in supernova remnants and the corona of stars (10 million K). The Indian Institute of Astrophysics (IIA), Bangalore, is in charge of the design and fabrication of the ultraviolet imaging telescopes of Astrosat.

40. Indians in Space

The impact of microgravity on materials and human body has been the subject of research in space in both manned and unmanned missions.

Two experiments were done on board a space capsule, launched by PSLV-C7 in 2007. The experiments in microgravity are designed to explore new phenomena and test basic theories on materials and their characteristics.

One of the experiments was isothermal heating furnace. It was a joint experiment by the Indian Institute of Science, Bangalore and Vikram Sarabhai Space Centre. It was designed to study the heating pattern that would be found on metals in microgravity. The other experiment was designed by the National Metallurgical Laboratory, Jamshedpur, to study nano crystals under microgravity.

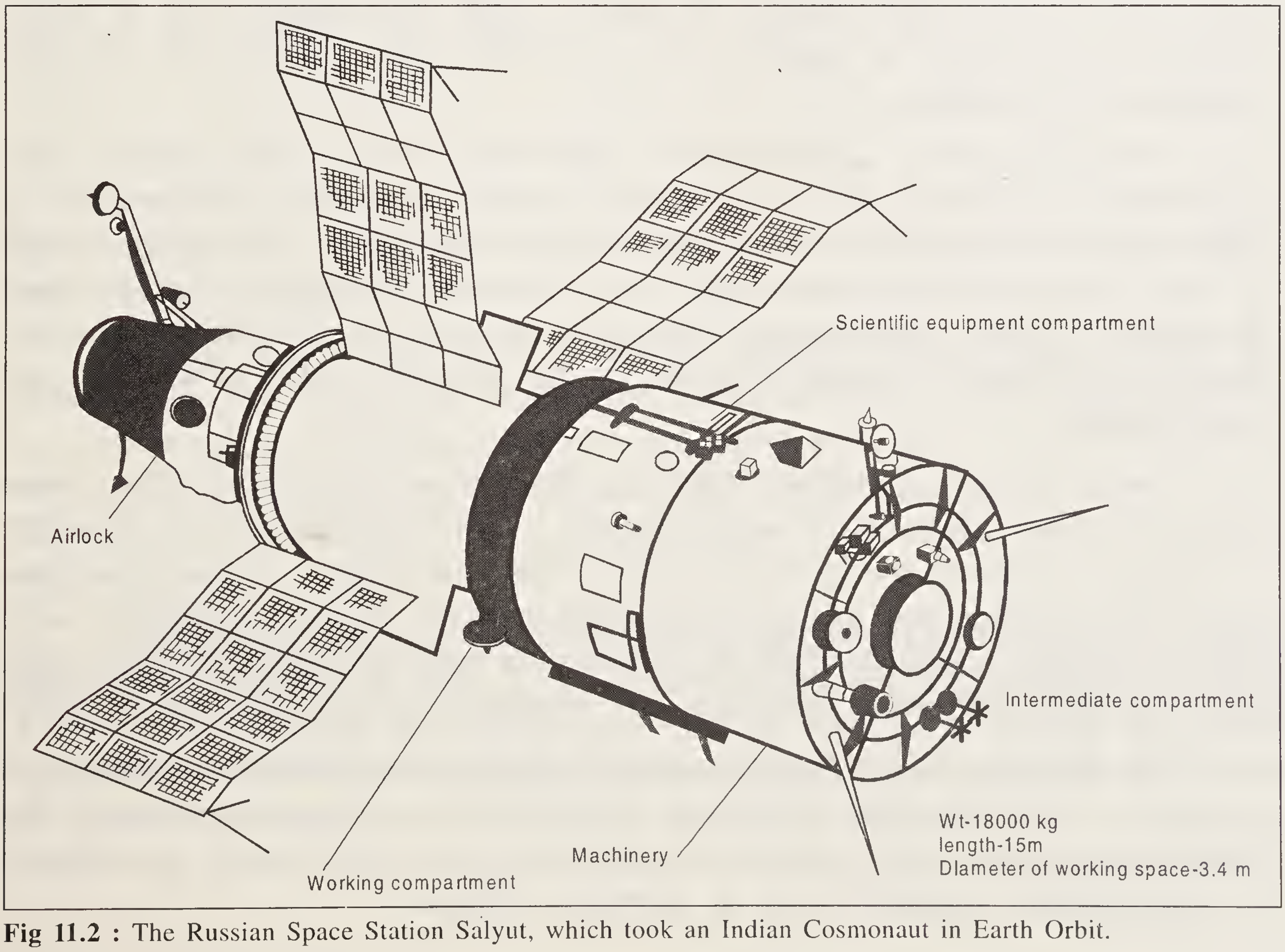


Fig 11.2 : The Russian Space Station Salyut, which took an Indian Cosmonaut in Earth Orbit.

Squadron Leader Rakesh Sharma, who went on board the Russian Salyut-7 in 1984, conducted an experiment related to the formation of a new alloy by heating silver and germanium in a furnace on board. (Fig. 11.2)

Alloys impossible to get on earth can be made in space. Glass and metal, for example, can be mixed. Crystals of great purity can be mixed. Germanium and silver have almost identical melting points and the new alloy can be of immense benefit in power transmission and other fields. The basic principle in getting the alloy is simple. In the virtual absence of gravity, the atoms of the mixing materials, while being cooled, cannot form a coherent crystalline structure but will result in what is known as an amorphous material which will be stronger than a regular crystalline structure possible under normal gravitational convection. Moreover, it is possible to undercool liquids in space without turning them into solids quickly. The mixture of smelted silver and germanium cooled below the solidification point and remained in its liquid form. This supercooling has some unusual qualities. The cosmonaut could take out the liquid alloy from the vessel before the cooling process started.

Though the impact of the virtual absence of gravity has not been fully understood, physical processes can now be observed from a unique perspective, where gravity is not dominant. Under microgravity conditions, gravity-related processes such as buoyancy and sedimentation would be different. Containerless positioning, handling and shaping of liquids would be possible only in space. Studying the processes in materials in space would pave the way for the next generation of materials.

The microgravity environment is ideal for the so-called critical point experiments. A critical point is the highest possible temperature and pressure at which the gas and liquid states are separated. For example, a 1-mm high sample on Earth will be 10 per cent denser at the bottom than at the top. In space the absence of density stratification allows the study of the critical point phenomena. Sulphur hexafluoride is generally chosen for the experiment as it is nontoxic and non-flammable.

Several new technologies, useful for future space applications, have been tested in various missions of foreign agencies. The ion thruster is an example. It can give ten times the power of today's chemical rockets. It can reduce the mass of the satellite and increase its payload capacity. New generations of solar cells can also be evaluated. Gallium arsenide solar cells are the likely choice since they have high conversion efficiency and resistance to the conditions of space.

The Russians have conducted many experiments on materials in space. At one time, a 220-hour long smelt was carried out in a furnace on board. The Shuttle missions have also conducted several experiments which include an evaluation of semiconductor materials such as cadmium telluride.

The long-term effect on materials in space has yet to be studied comprehensively. Missions of short duration can only indicate but cannot definitely state the nature of the impact. Hence attempts are under way to keep the sample for a long duration.

Views of the First Doctor in Space

Ever since life forms evolved on our planet, they have been subject to the pull of gravity. Only since the Space Age started 50 years ago, have humans escaped the pull of gravity to a large extent. Dr Boris Yegorov, the word's first doctor cosmonaut who had been on the Voskhod mission, the first multimanned spacecraft, which took three persons on board told the author that microgravity was a much misunderstood phenomenon. It does not mean complete absence of gravity. In fact, at the height they orbited, the Earth's gravity was still as strong as it was on the ground level. But inside the spacecraft, because of its speed, there was microgravity, which caused the strange feeling of weightlessness. That is why we see the cosmonauts or astronauts floating around inside spacecraft, where, there is no up or down, no horizontal or vertical. During the launch and the return to the Earth, they are subjected to very heavy gravity forces.

Microgravity, which is difficult to create on the Earth, could be used to study the human body. Even though Yegorov was in orbit only for about a day, he was able to envisage the consequences of a longer term stay in space for humans. He said in space there was no need for a strong bone structure. And muscles get reduced. The calcium in bones becomes superfluous. The calcium content of the urine goes up by 50 per cent. Bones would fracture easily, if subjected to sudden pressure, as in the case of elderly people. Yegorov said there was no medicine to stabilise the body's calcium. After a stay of about a month or so, returning cosmonauts and astronauts had to be carried by ground teams after landing. The spine itself extends by 4 cm in a 1.75. metre tall person. It will eventually regain its dimensions after the cosmonauts' return.

Yegorov said it was better to prepare oneself, while in space to face the conditions on the ground. For this purpose, penguin-like suits are sometimes worn to promote blood circulation. Yet the cosmonaut said that it was not good to alternate frequently from microgravity and normal gravity. The more one stayed in space, he thought, the better it was. His predictions about the challenges in manned missions have come true.

Cosmonaut Rakesh Sharma experienced prolonged microgravity in the Russian space station, Salyut-7 on April 3, 1984. He was launched into space by the Soyuz T 11 rocket. His pulse rate during lift-off jumped from 72 to 102 but after about seven minutes came down to 84 as expected. The pulse rate was less than those of his colleagues who were directly in charge of controls.

Within nine minutes he and his colleagues, Malyshev, Gennadi Strekalov were in low Earth orbit of about 230 km. When they were about to complete 17 orbits, they were docked with Salyut-7. Three hours after the docking, the cosmonauts floated into Salyut. They were greeted by three cosmonauts already in the station for 60 days. During his stay, Rakesh had a new menu which included mango and pulav. Some of the items were specially prepared by the Defence Food Research Laboratory.

After completing 125 orbits, the visiting cosmonauts returned by Soyuz-10 which had remained attached to Salyut-7. Soyuz-10 separated from Salyut on April 11. After jettisoning the transfer module and the equipment module, they re-entered the atmosphere in the descent module. The main parachute opened at about 7 km automatically and the module touched down at zero speed on fresh snow.

Rakesh Sharma did yoga exercises including *pranayama, stithikaran vyayama* and three *asanas* like *padahastha, parimitra trikona and ustra*. He also participated in biomedical experiments to determine the conditions of cardiac, vascular and vestibular functions under microgravity. He had used the vector cardiograph developed by the Indian Institute of Aviation Medicine to study the bioelectricity activity of the heart.

Two women of Indian origin have distinguished themselves as outstanding American astronauts. Kalpana Chawla, who tragically lost her life while returning from a successful visit to the International Space Station in 2003, has become an icon of adventure in India.

Kalpana Chawla : An Icon Of Adventure

Kalpana Chawla (1961-2003), Indian American astronaut, is an icon of adventure for India's younger generation. She was a mission specialist, one of the crew of seven, who lost their lives, while returning home in a space shuttle after a successful mission to the International Space Station in 2003.

Kalpana was a science graduate from the Punjab Engineering College, Chandigarh. She did her MSc in aerospace engineering in the United States and later got a PhD in the subject from the University of Colorado. She worked for NASA's Ames Research Centre. She married Jean Pierre-Harrison in 1983 and became a naturalised US

citizen in 1990. She got a commercial pilot licence and joined NASA in 1995. She was selected in 1997 as a member of the shuttle (STS-87) team and logged 375 hours in space. She deployed a satellite, which malfunctioned and an astronaut had to do a spacewalk to capture it. However, after a five-month investigation, the cause of the failure was traced to software problems, which were later changed.

Kalpana was selected for another shuttle mission, which was delayed for several reasons, including the discovery of cracks in the engine flow lines. On their return from space into the atmosphere, some of the tiles that protect the spacecraft from the heat of re-entry, gave way and all of the crew tragically lost their lives, in the fire that engulfed them.

NASA dedicated a super computer to her memory. A hill on Mars and asteroid 51826 were named after her. In India thousands of young people as well as leaders mourned her untimely death. And India's first exclusive weather satellite has been named Kalpana-1.

An avid bird-watcher and a lover of music (she carried 24 CDs of songs), she famously remarked, "The whole world is my native land"!

World Records by Sunita Williams

Recenly, Sunita Williams, (b.1965), an American astronaut of Indian and Slovenian origin, became world famous. She went into space aboard a shuttle on 10 December 2006 and returned on 22 June 2007. As a flight engineer of the International Space Station, she set up world records, by staying in space for 195 days – the longest single spaceflight for a woman astronaut — surpassing the previous record of 188 days set up by Shannon Lucid in 1996 and by doing four space walks by a woman outside the space station, clocking a total of 29 hours and 17 minutes, exceeding the record set earlier by Kathryn Thornton. And she ran on a tread mill on board the ISS completing the gruelling 42-km Boston Marathon in four hours and 23 minutes.

A keen sportsperson, Sunita is fond of swimming, running, biking, windsurfing and snowboarding. She emphasised physical fitness to be an astronaut.

Sunita was born in Euclid, Ohio and took a Bachelor's Degree in Physical Sciences from the US Naval Academy and Master's in Engineering Management from the Florida Institute of Technology. She worked as an instructor at the Naval Test Pilot School. She was selected to the astronaut team in 1988. She had had

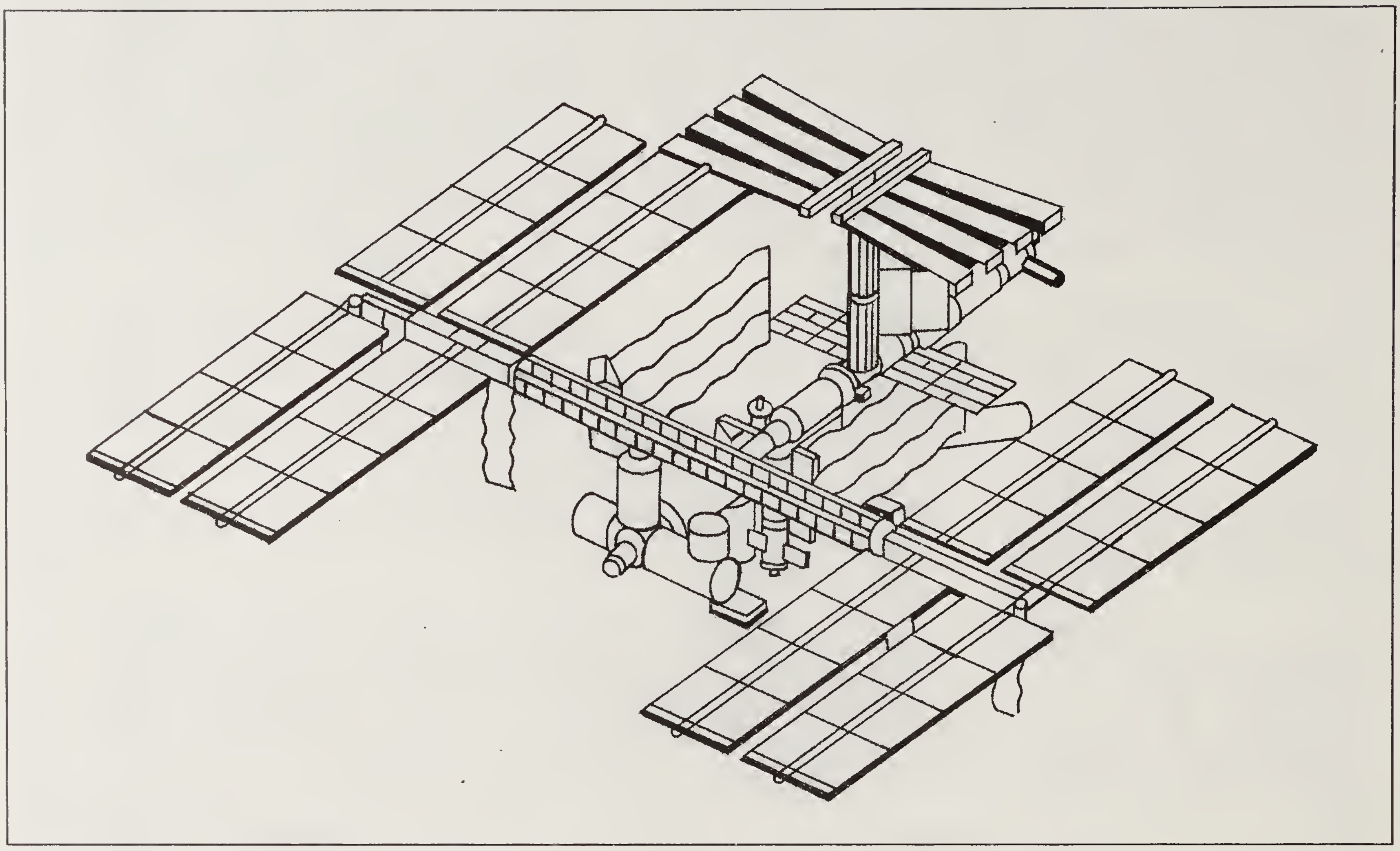


Fig 11.3 : The International Space Station.

eight years of intensive training including several hours in a special pool of water to simulate space walking. She also learnt how to operate the robotic arm in space.

Sunita had taken a letter in Hindi written by her father, Deepak Pandya, and praised him for encouraging her to become an astronaut and thereby fulfil her childhood dream.

She also took with her a copy of the Bhagvad Gita, and an idol of Ganesha. While in space, she could not resist asking for tasty food and relished Indian *chhole, paalak paneer* and *halwa* and longed to return to Earth and take a walk on the beach with her husband and pet dog.

GLOSSARY

Acceleration	:	Rate of change of velocity.
Aeronomy	:	Study of upper regions of the atmosphere.
Angstrom	:	A unit of length, used mainly to express short wavelengths. Ten billion angstroms equal one metre.
Antenna	:	A conductor for radiating or receiving radio waves.
Apogee	:	The point at which a satellite is farthest from the Earth. (Opposite of perigee)
Atmosphere	:	The body of gases surrounding the Earth, a planet or a star.
Attitude	:	The position or orientation of a rocket or a satellite.
Bandwidth	:	A 'path' required for the transmission of information, expressed in units of frequency.
Beamwidth	:	The width of the beam of radiation shaped by a communications antenna (measured in degrees).
Bipropellant	:	A rocket propellant consisting of two separate chemicals (fuel and oxidant) and separately into the combustion chamber.
Bit	:	Binary Digit of 1 or 0 used to code information.
C-Band	:	Radio frequency band of 3.9 to 6.2 GHz with wavelengths of 4.84 to 7.69 cm.
Clarke Orbit	:	Another name for geosynchronous orbit named after Arthur Clarke who first suggested it.
Coasting	:	Rocket in motion after firing its engines.
Colour Infrared Film	:	A film sensitised to to green, red and near-infrared instead of blue, green and red wavelengths of conventional colour films. Healthy vegetation is

shown as bright red or pink.

Communication : L-band 1-2 GHz S-band 2-4 GHz

Frequencies : C-band 4-8 GHz X-band 8-12 GHz

Ku-band 12-18 GHz K-band 10-36 GHz

Computer : A machine for quick calculations of data fed into it. It can also be programmed to take certain decisions.

Cosmic Rays : Extremely high-energy sub-atomic particles which bombard the atmosphere from outer space.

Cosmos : The known and theoretical universe.

Count-down : The time period in which a sequence of events is carried out to launch a rocket.

Cryogenic Propellant : A rocket fuel which is liquid only at very low temperature.

Data : Any information usually sent in the form of binary bits.

Digitise : Conversion of data (e.g. maps) into a digital format.

Domestic Satellite : A satellite used for internal communication of a country.

Doppler Shift : Shift in frequency with which energy reaches a receiver, when the source of radiation such as a satellite is in motion. Used in tracking satellites/ rockets.

Earth Sensor : A device used to establish a spacecraft's attitude relative to the Earth.

Earth Station : Antennas and related equipment on the ground that contact a satellite.

E.I.R.P. : Equivalent Isotropic Radiated Power, it is the equivalent power that would have to be radiated by an antenna uniformly in all directions from the beam centre.

Electrojet : Shower of electrons at the equatorial region.

Electromagnetic Energy : Energy propagated in the form of a radiation

		disturbance in the electrical and magnetic fields.
Ellipse	:	Orbit described by a planet around the sun.
Escape Velocity	:	Velocity of a body to escape the gravitational pull of a surface.
Exhaust Velocity	:	The speed at which gases force themselves out of the nozzle of a rocket.
Facsimile	:	Technique to reproduce an exact copy of a document or picture over a distance.
Footprint	:	The projection of a satellite's antenna beam on the Earth's surface.
Frequency	:	Rate at which a periodic signal repeates itself. The unit of frequency is called hertz.
Frequency Reuse	:	Using the same frequency more than once in the same satellite beam or by using several spot beams.
g	:	Acceleration equal to the acceleration of gravity, about 32.2 feet per second square at sea level; used as a unit of stress measurement for bodies undergoing acceleration (a unit of force exerted on a body by gravity. The Earth's gravity exerts a force of one g.)
Galaxy	:	A group of billions of stars and other celestial bodies of which the solar system is a part.
Gamma rays	:	High-energy radiation of very short wavelengths, produced in outer space or in the sun.
Geographic Information System (GIS)	:	A computer-based information system that can input, manipulate, and analyse geographically referenced maps as well as tabular data. Satellite imagery is used in GIS for natural resource management.
Geosynchronous orbit (GEO)	:	A circular orbit above the Earth's equator, where

a satellite has the same period of rotation as that of the Earth at a height of 35,786 km.

Geostationary Transfer Orbit (GTO) : An elliptical Earth orbit used for transfer of a spacecraft from a lower orbit to GEO.

Geostationary satellite : A satellite which appears stationary in relation to the Earth, but is synchronous with the Earth's rotation.

Giga Hertz (GHz) : Billion Hertz.

Gimbal : A device with two mutually perpendicular and intersecting axes of rotation, giving free angular movement in two directions, on which an engine or other object may be mounted.

Gyroscope : A guidance system (rapidly spinning wheel) suspended in a special frame; the axis of its rotation remains the same irrespective of the frame's movement.

Hertz : One cycle of a wavelength per second, named after Heinrich Hertz.

High Frequency (HF) : 3-30 MHz

Hypergolic propellants : Propellants which ignite spontaneously when mixed

Horizon Sensors : Used to determine the centre of the Earth by detecting its infrared emission.

Instataneous Field of View (IFOV) : For a sensing device, the area covered at a single moment described either as the angle through which the sensor gathers radiation or the area at a specified altitude.

Infrared : Electromagnetic radiation pertaining to energy in the 0.7-100 micrometre wavelength region. Often subdivided into near-infrared (0.7-1.3) micrometres), middle-infrared (1.3-3 micro.met.) and far-infrared (7.0-15.0 micrometres). Far infrared is also known as thermal or emissive infrared.

Inertial guidance	:	Self-contained steering system that corrects deviations in a rocket's course, speed and range.
Internet	:	A network of computer networks spread across several countries; it provides information on a wide range of topics.
Ionosphere	:	The atmosphere shell known for its weakly ionized plasma, which reflects radio waves sent from the Earth.
Light Year	:	Distance travelled by light in one year at the velocity of about 3,000,000 km per second.
Low Earth-Orbit (LEO)	:	A nominally circular orbit of low altitude and short period (about 90 minutes).
Long Waves	:	Low frequency waves that travel along the ground for considerable distance.
Lyman-Alpha radiation	:	The radiation emitted by hydrogen at 1216 Angstrom, first observed in the solar spectrum - by rocket-borne spectrographs.
Magnetic Dip	:	The angle between the horizontal and the direction of a line of force of the Earth's magnetic-field at any point.
Magnetic Equator	:	An imaginary line on the surface of the Earth connecting all points at which the magnetic dip is zero.
Magnetometer	:	An instrument used in the study of geomagnetism for measuring a magnetic element.
Magnetosphere	:	The outer boundary of the geomagnetic field as defined by the solar wind.
Medium Frequency	:	Radio waves used for transmission of programmes over short distances.
Mega Hertz (MHz)	:	One Million Hertz.
Micro-g (Weightlessness)	:	A condition in which the effect of gravity is not experienced by an observer within the spacecraft.
Micrometre	:	One millionth of a metre. (The term micron used to denote it was discontinued by an international agreement in 1967).

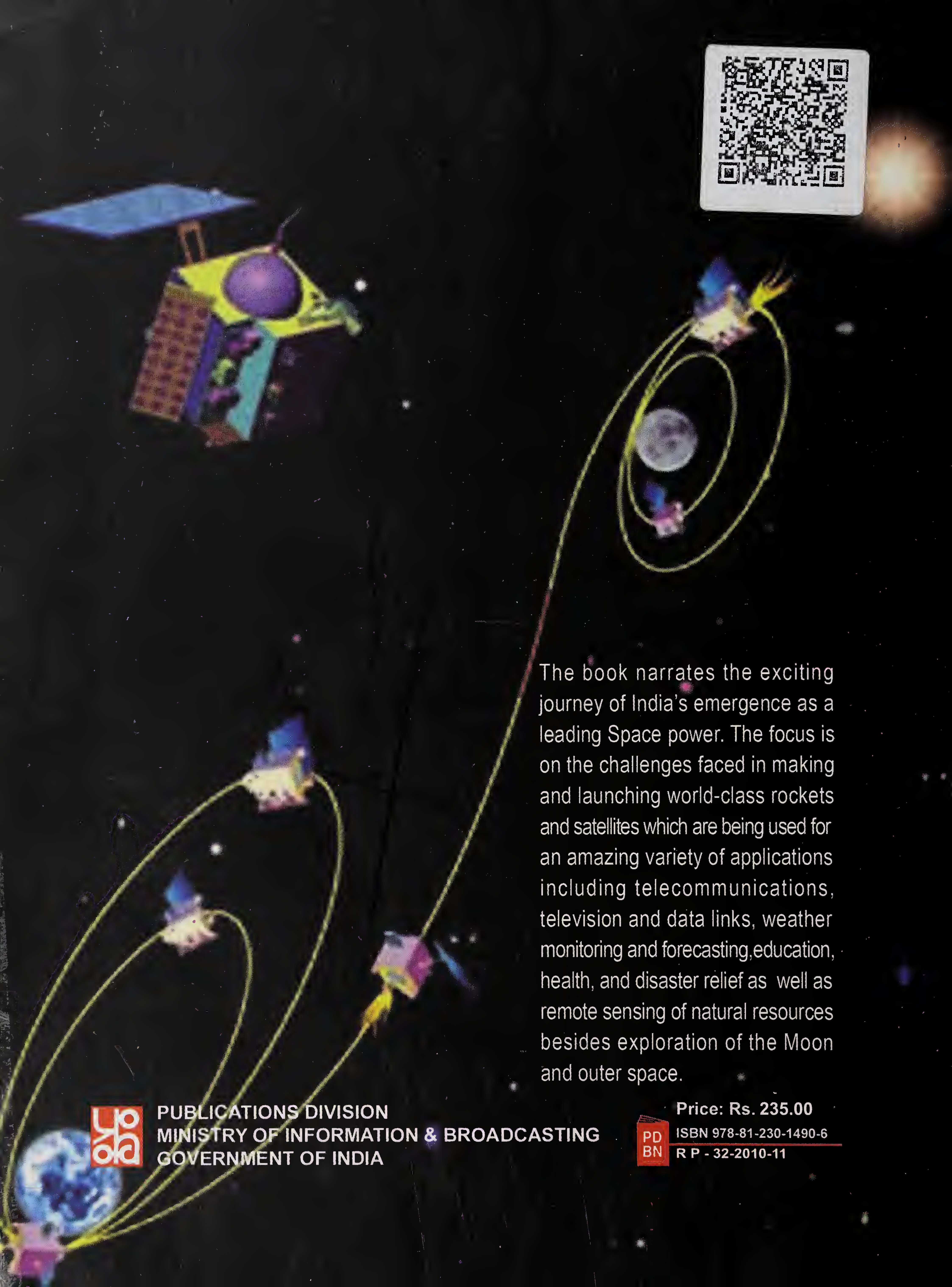
Microwave	:	Radiowaves about 1000 Mega Hertz which travel straight as lightwaves, used in telecommunication.
Microwave Background	:	Microwave radiation surrounding us from all sides, considered to be the remnant of the Big Bang.
Module	:	A self-contained building-block of a spacecraft or any structure.
Momentum Wheel	:	A wheel in a three-axises stabilised spacecraft used to provide gyroscopic stability and attitude control.
Monopropellant	:	A single chemical propellant
Multispectral Scanner	:	A device to record radiation emitted or reflected at different wave-lengths by objects.
Multiple Access	:	Access to a satellite by many ground sations.
Netwton's Laws	:	First Law: If a body in motion is not acted upon by an external force, its momentum remains constant. Second Law: Rate of change of momentum of a body is proportional to the force acting upon the body and is in the direction of the applied force. Third Law: For every force acting upon a body, there exists a corresponding force of the same magnitude exerted by the body in the opposite direction.
N	:	A symbol of force indicating the force required to move one kg of mass to one metre a second per second.
Nanometer (nm)	:	Billionth of a metre.
Nanosecond	:	One billionth of second.
Optical Fibres	:	Extremely thin and pure glass fibres used to guide lightwaves.
Orbit	:	The path of a body under the influence of a gravitational or other force to go around the Earth or other body in an orbit.
Omnidirectional antenna	:	An antenna which provides coverage in almost all directions.

Orbital Period	:	The interval between successive passages of a satellite.
Panchromatic	:	Refers to the sensitivity of films to a single broad band (e.g. the entire visible part of the spectral bands).
Payload	:	That which a rocket of satellite carries over and above what is necessary for its flight. Includes application-oriented instruments such as cameras on the satellite.
Perigee	:	The point of nearest approach of a satellite to the Earth.
Pitch	:	Axis parallel to the north-south direction of the Earth.
Plasma	:	An electrically conductive gas consisting of neutral particles, ionized particles and free electrons but which is electically neutral taken as a whole.
Propellant	:	Solid or liquid fuel that gives thrust to a rocket.
Radio Telescope	:	An instrument which receives and amplifies radio waves from outer space.
Radio Spectrum	:	Radio frequency range as specified by the international Telecommunication Union: **VLF 3-30 KHz** **HF 30-300 Khz** **MF 300-3000 KHz** **HF 3-30 MHz** **VHF 30-300 MHz** **UHF 300-3000 MHz** **SHF 3-30 GHz** **(V: very; U: ultra; L: low; M: medium; H: high; F: frequency).**
Real Time	:	Time in which recording of events is simultaneous with the events.
Red Shift	:	The light from distance galaxies is shifted in wavelength towards longer wavelengths (red in

		the visible spectrum) implying an expanding Universe.
Remote Sensing	:	Process by which features or objects on the Earth are sensed remotely by satellites or rockets.
Reaction Wheel	:	A wheel used to control the attitude of three-axis stabilised spacecraft.
Resolution	:	The ability of a remote sensor to render a sharply defined image. Common types of resolution are: **ground resolution** (the minimum distance between two or more adjacent features or a minimum size of a feature, usually measured in metres); **image resolution** (expressed in terms of lines per millimetre); and **thermal resolution** (in terms of minimum temperature difference between two objects).
Riometer	:	Measures the absorption of radio waves in the ionosphere.
Roll axis	:	Lies in the direction of the motion of a satellite.
S-Band	:	Radio frequency band of 1,550 to 5,200 MHz with wavelengths of 5.77 to 19.35 cm.
Semi-major axis	:	One of the halves of the major axis of an orbit.
Solar Corona	:	The outer visible envelope of the sun seen during total solar eclipse.
Solar wind	:	A stream of charged particles constantly moving outward from the sun blowing past the Earth's magnetic envelope.
Sonic Speed	:	The speed of sound, about 1216 kmh also called Mach-1.
Sounding Rocket	:	A rocket with sensors to explore the atmosphere.
Space	:	Universe outside the Earth's atmosphere.
Specific impulse	:	A performance indicator of a rocket propellant.
Spectral Signature	:	Quantitive measurement of the properties of an object at one or several wavelength intervals.
Spectrometer	:	A radiometer with a dispersive element (prism) that enables characteristics of the incedent

		radiation to be determined as a function of wavelength.
Spread Spectrum	:	Advanced technique in satellite communication; permits simultaneous access to the transponder bandwidth, where the wanted signal alone is derived after unwanted signals are spread over the bandwidth.
Sunsynchronous orbit	:	Nominally a retrograde, quasi-polar near-Earth orbit in which a satellite crosses the equator always at the same local time and appears at the same sun angle.
Sun sensor	:	A sensor that locks on to the sun for purpose of navigation.
Supernova	:	A star which explodes giving of most of its energy.
Swath Width	:	Linear ground distance covered by a multispectral scanner in the across-track direction.
Telecommand	:	Commands sent to a performance of a rocket or satellite and transmission of information to a ground station.
Telemetry	:	Measurement of the performance of a rocket or satellite and transmission of information to a ground station.
Three-axis-stabilised satellite	:	A satellite that is kept stable with the help of an attitude control system aligned to its pitch, roll and yaw axes.
Thrust	:	The force which propels a rocket.
Time Division Multiple Access	:	An advanced telecommunication technique which enables several stations to time-share a satellite's frequency.
Tracking	:	The process of following the movement of a satellite or rocket by radar or radio.
Trajectory	:	Path of a rocket or satellite.
Transducer	:	A device actuated by energy from one or more transmission systems and of supplying related energy to one or more other transmission systems (e.g. microphone).
Transponder	:	A receiver-cum-transmitter which will transmit

		signals automatically when triggered by an interrogating signal.
Uplink	:	Communication path from an Earth station to a satellite.
Ultra-violet radiation	:	Electromagnetic radiation shorter in wavelength than the visible radiation but longer than X-rays.
UHF	:	Ultra-high frequency band of 300 to 3000 MHz with wavelength between 10 and 100 metres.
VHF	:	Very high frequency band of 30 to 300 MHz with wavelengths between 1 and 10 metres.
X-Band	:	Radio frequency band of 5200 to 11,000 MHz with wavelengths of 2.75 to 5.77 cm.
Yaw (axis)	:	Lies in a (satellite's) direction to the centre of the Earth.



The book narrates the exciting journey of India's emergence as a leading Space power. The focus is on the challenges faced in making and launching world-class rockets and satellites which are being used for an amazing variety of applications including telecommunications, television and data links, weather monitoring and forecasting,education, health, and disaster relief as well as remote sensing of natural resources besides exploration of the Moon and outer space.

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